Microwave Devices & Radar

LECTURE NOTES
VOLUME IV

by Professor David Jenn

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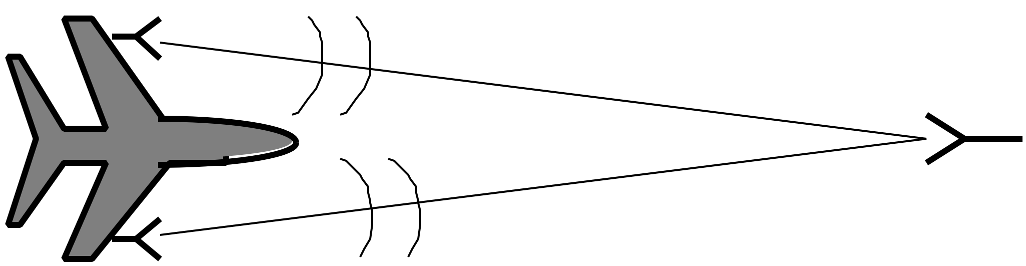

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Special Radar Systems and Applications

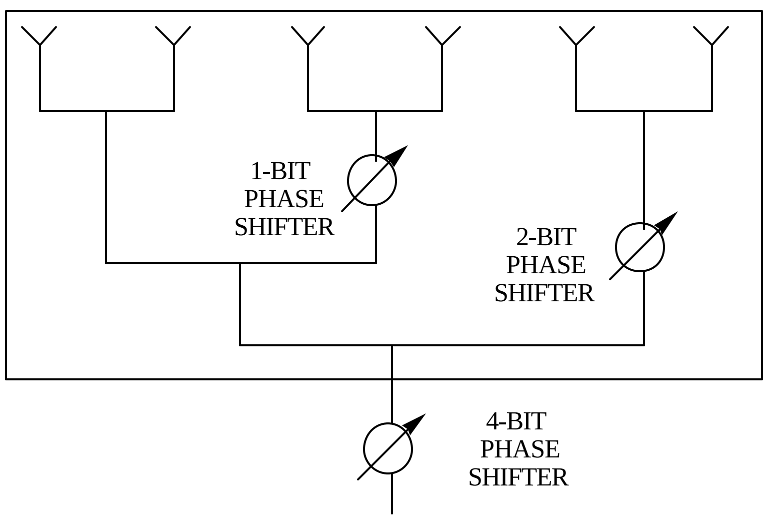
- Firefinder, Patriot, SPY-1, AN/APS-200, and SCR-270 radars
- Harmonic radars
- Synthetic aperture radar (SAR)
- Inverse synthetic aperture radar (ISAR)
- Stepped frequency radar
- Ultra-wideband radar (UWB)
- Radar electronic countermeasures (ECM): Crosseye; sidelobe cancelers and blanking; chaff
- HF over the horizon (OTH) radar
- Laser radar
- Ground penetrating radar (GPR)
- Doppler weather radar
- Bistatic radar

AN/TPQ-37 Firefinder Radar

Firefinder Radar Antenna (1)

Based on the concept of phase-steered subarrays: The array and subarray factors are scanned individually. The array factor has 4-bit phase shifters, whereas the subarray pattern is scanned using 2-bit phase shifters. The four possible "phase states" for the subarray are:

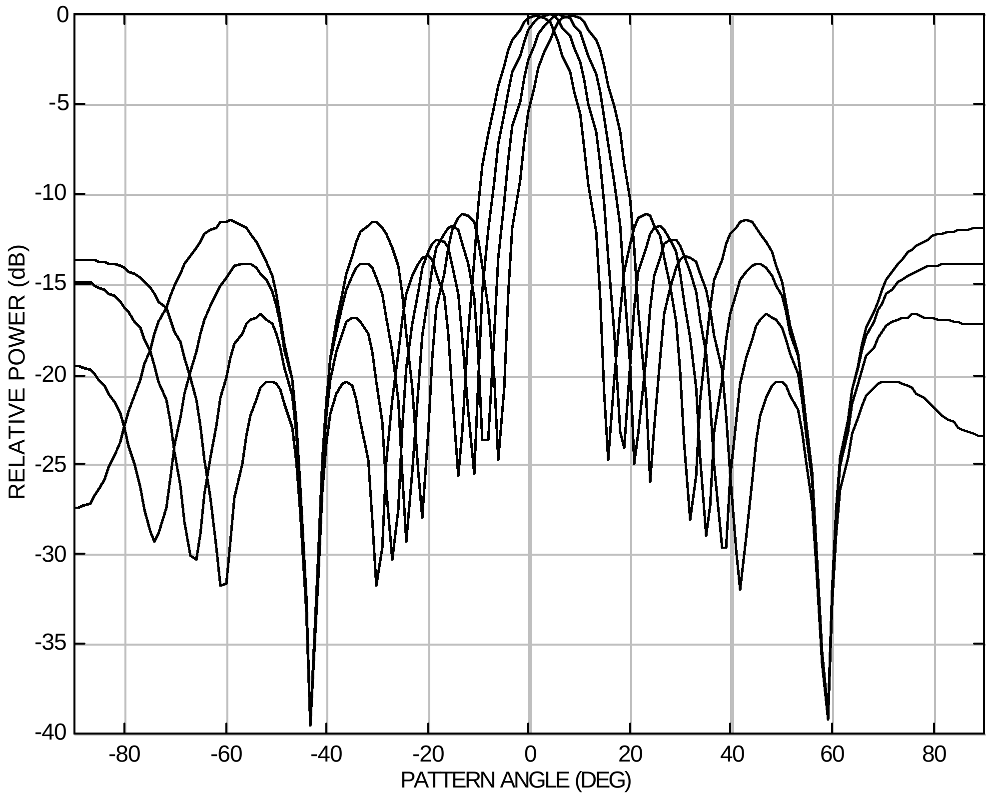
Phase State	Dipole Output Phase (Degrees)					
	1	2	3	4	5	6
1	0	-20	-19	-39	-17	-37
2	0	-20	-19	-39	-59	-79
3	0	-20	-61	-81	-101	-121
4	0	-20	-61	-81	-143	-163



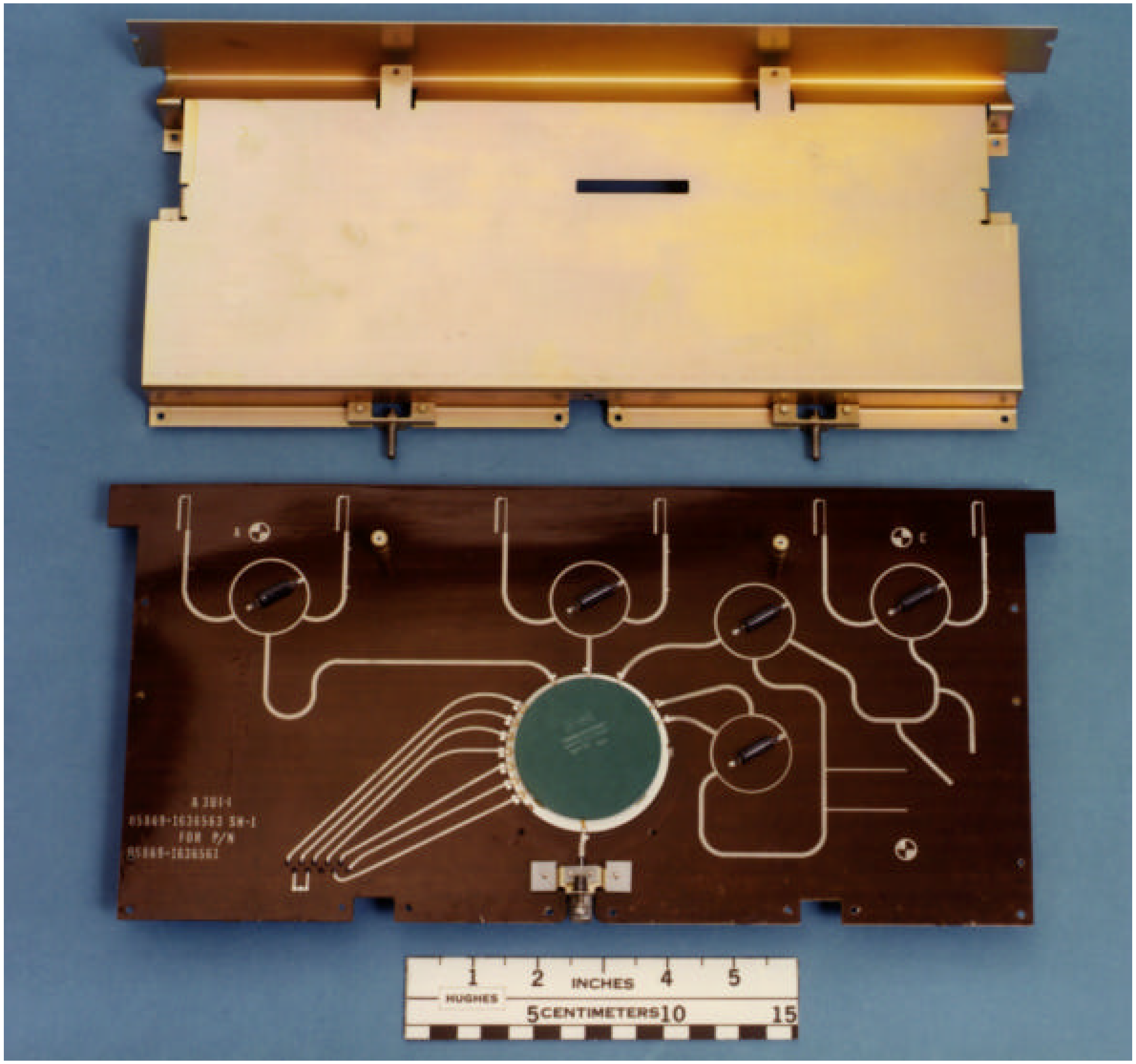
SIX-ELEMENT
SUBARRAY

Firefinder Radar Antenna (2)

Patterns of the six-element subarray (four possible phase states)



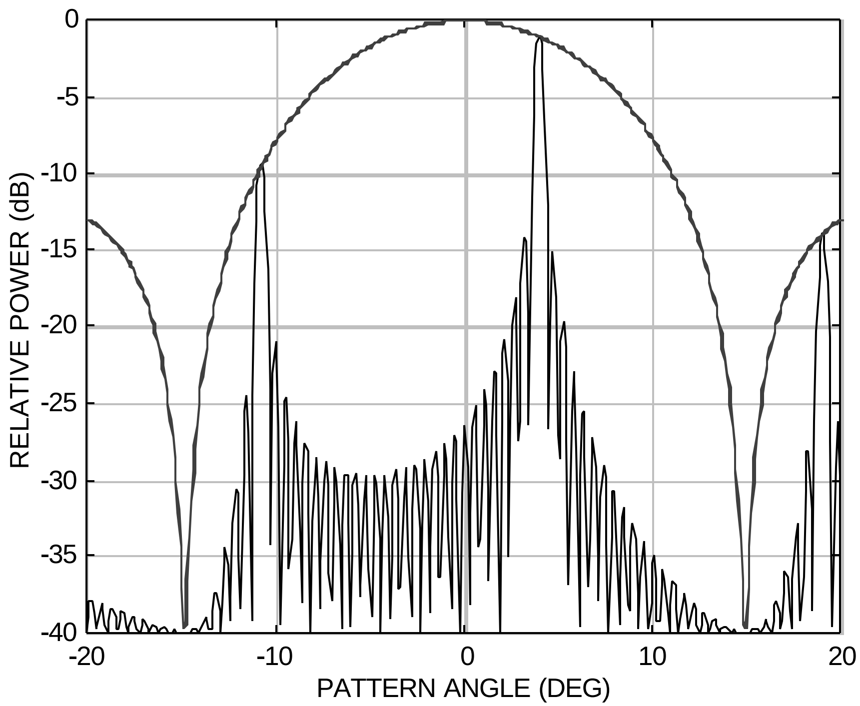
AN/TPQ-37 Subarray



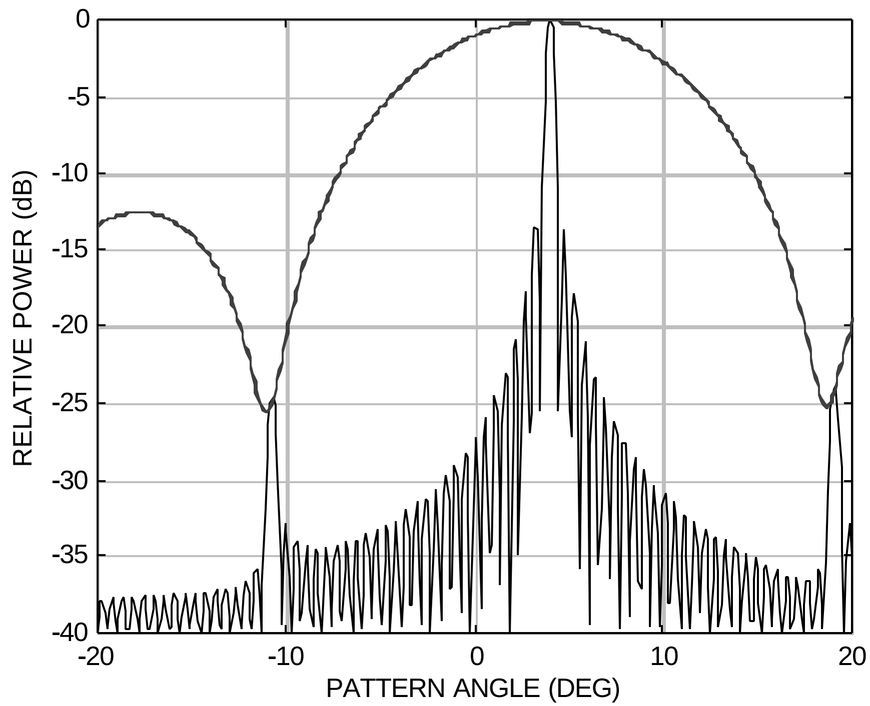
Firefinder Radar Antenna (3)

Array patterns with and without subarray scanning ($q_s = 4^{\circ}$). The dashed curve is the subarray pattern.

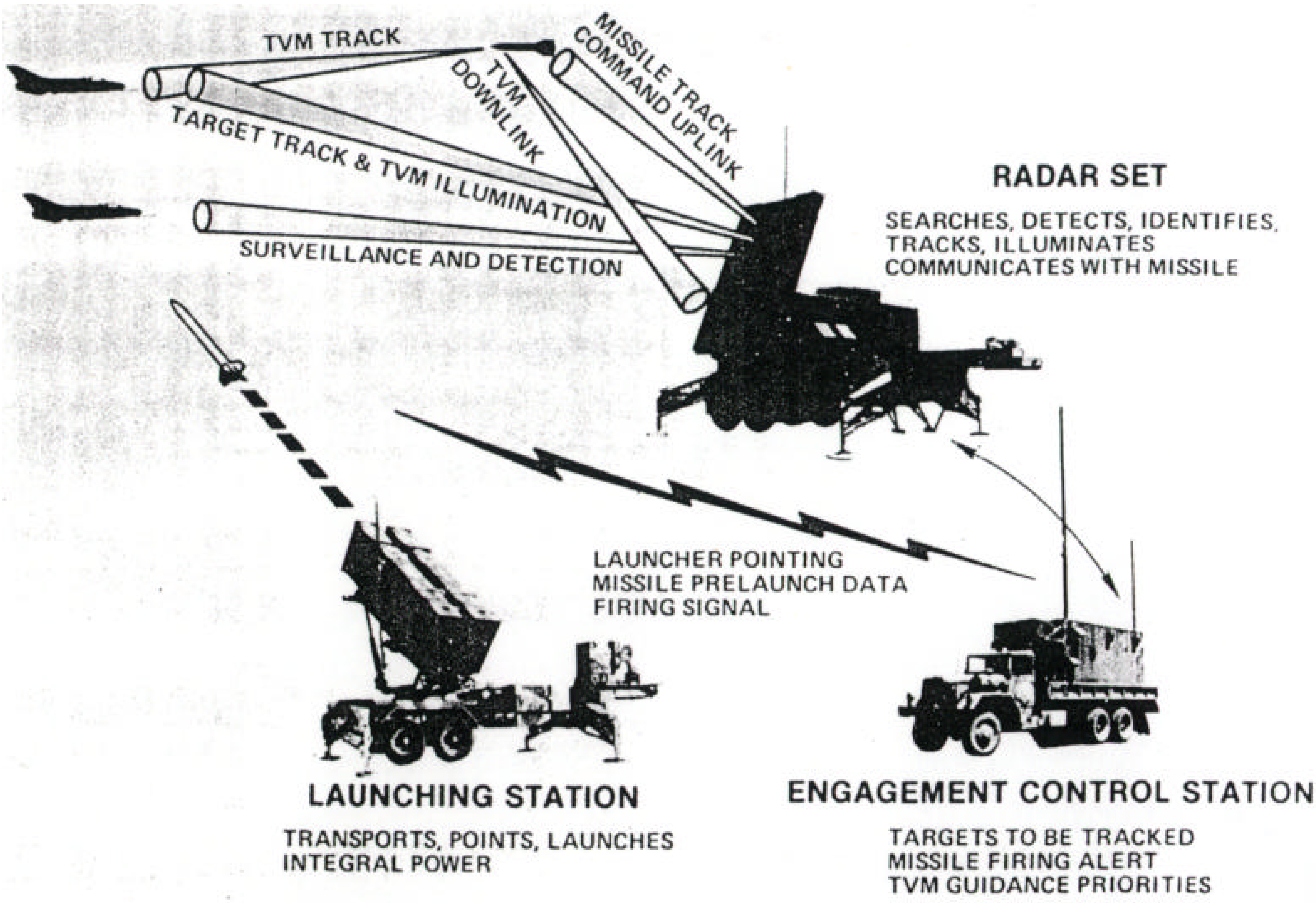
WITHOUT SUBARRAY SCANNING



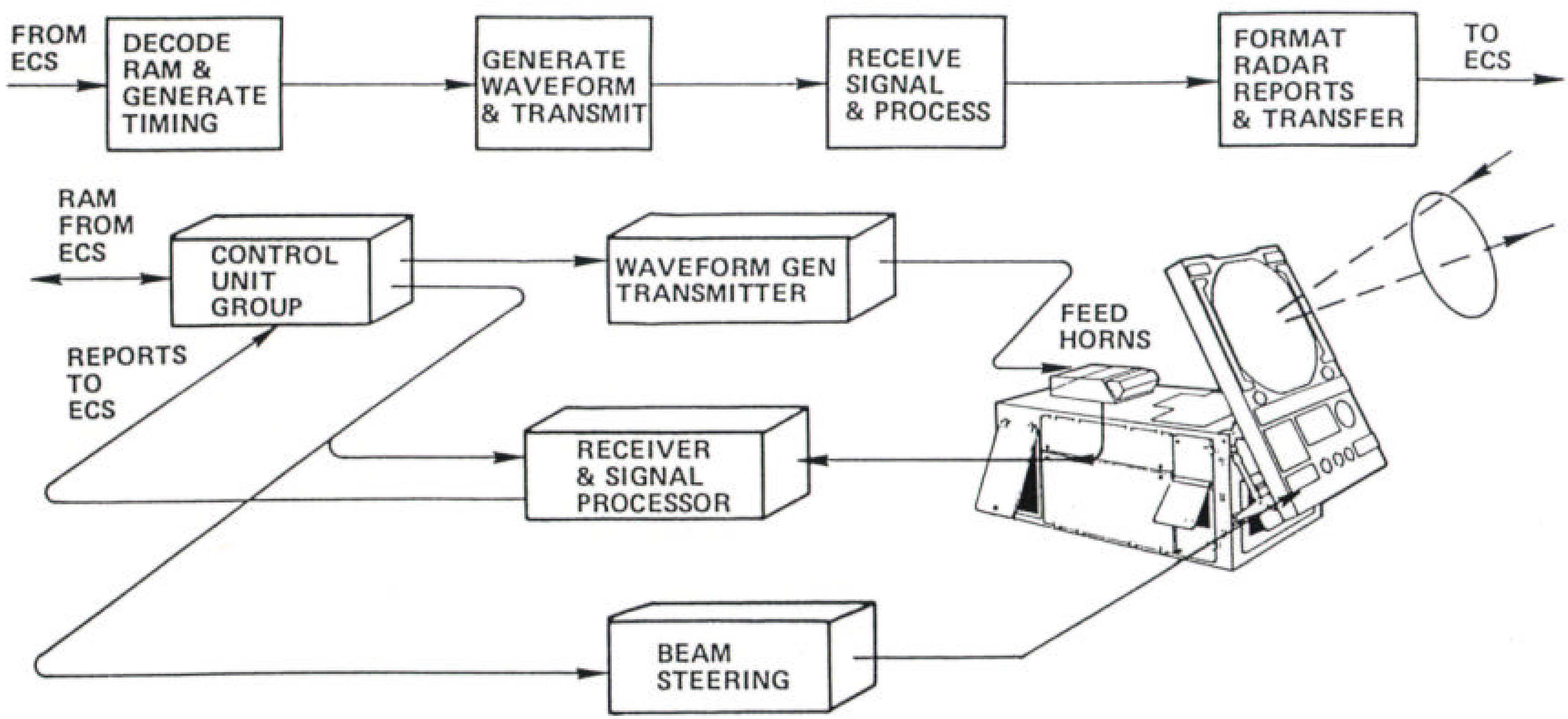
WITH SUBARRAY SCANNING



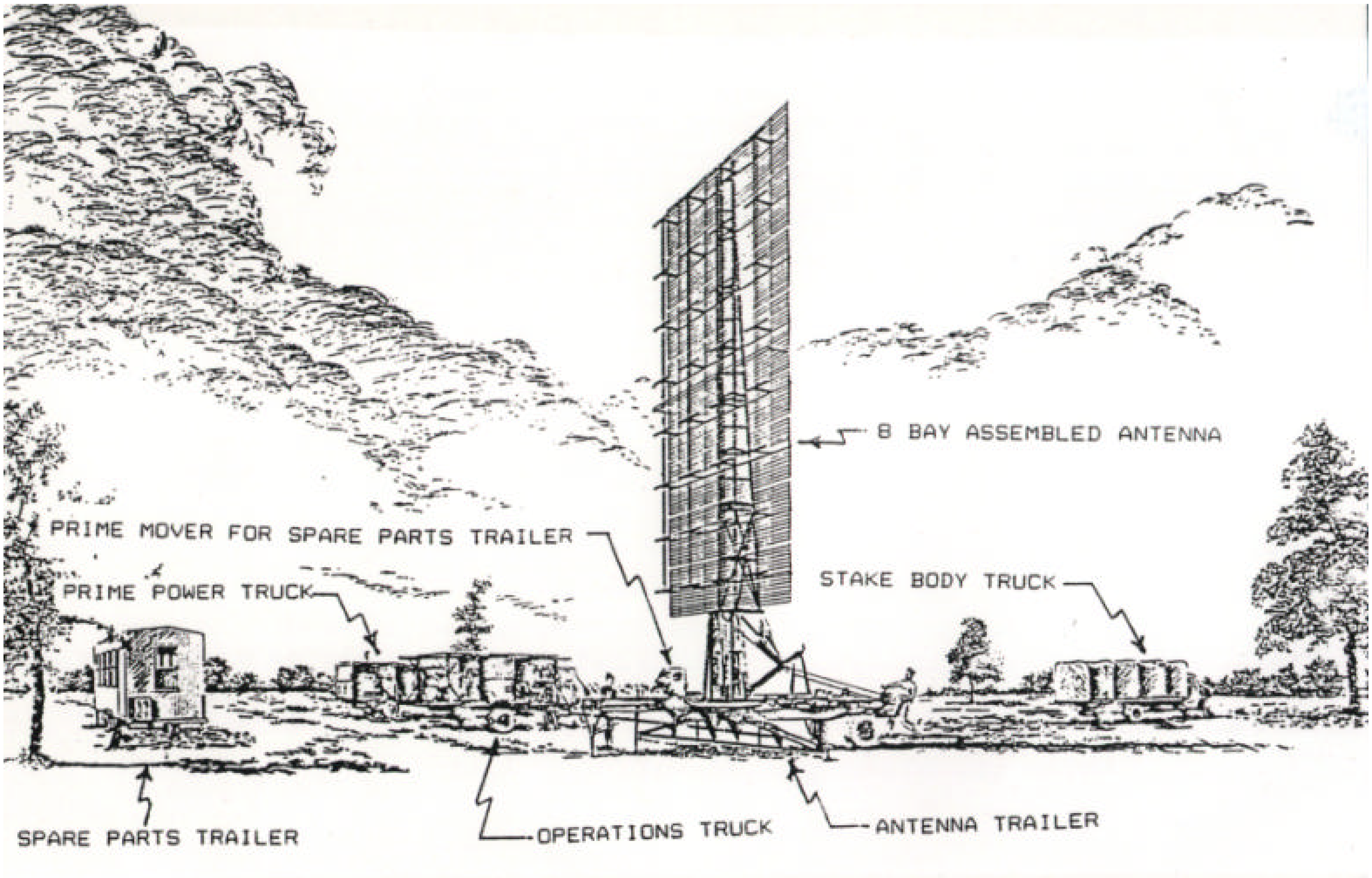
Patriot Air Defense Radar (1)



Patriot Air Defense Radar (2)



SCR-270 Air Search Radar



SCR-270-D-RADAR

Detected Japanese aircraft approaching Pearl Harbor.
Dipole array was tuned by maximizing the scattering from a metal propane storage tank.
Performance characteristics:

SCR-270-D Radio Set Performance Characteristics
(Source: *SCR-270-D Radio Set Technical Manual, Sep. 22, 1942*)

Maximum Detection Range	250 miles
Maximum Detection altitude	50,000 ft
Range Accuracy	± 4 miles*
Azimuth Accuracy	± 2 degrees
Operating Frequency	104-112 MHz
Antenna	Directive array **
Peak Power Output	100 kw
Pulse Width	15-40 microsecond
Pulse Repetition Rate	621 cps
Antenna Rotation	up to 1 rpm, max
Transmitter Tubes	2 tridoes***
Receiver	superheterodyne
Transmit/Receive/Device	spark gap

* Range accuracy without calibration of range dial.
** Consisting of dipoles, 8 high and 4 wide.
*** Consisting of a push-pull, self excited oscillator, using a tuned cathode circuit.

SPY-1 Shipboard Radar

SPY-1 is a multifunction 3-D phased array radar with the following characteristics:

- Four large (12.8 feet) antennas providing hemispherical coverage
- Each array has 4480 radiating elements (140 modules)
- Electronically scanned (non-rotating antennas)
- Frequency is S-band (3.1 - 3.5 GHz)
- Peak power 4 - 6 MW
- Radar resources are adaptively allocated to counter a changing hostile environment

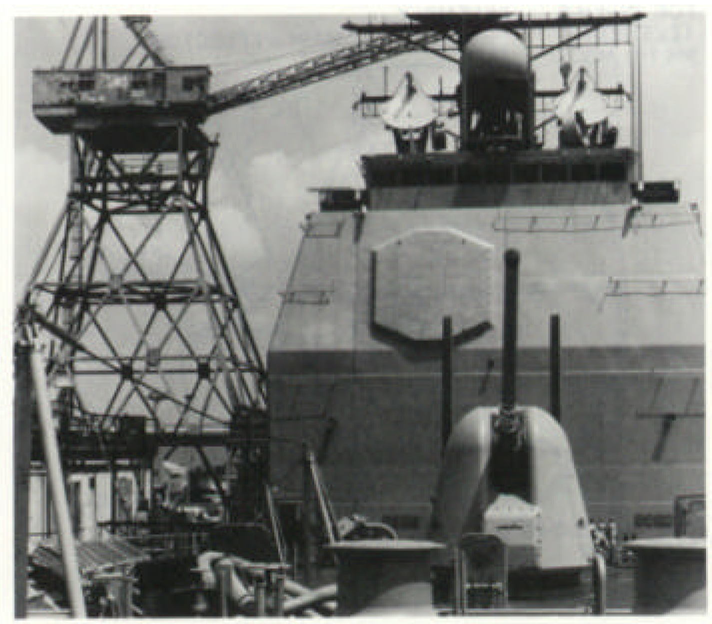
Primary functions:

- Tracking
- Fire control (missile guidance)

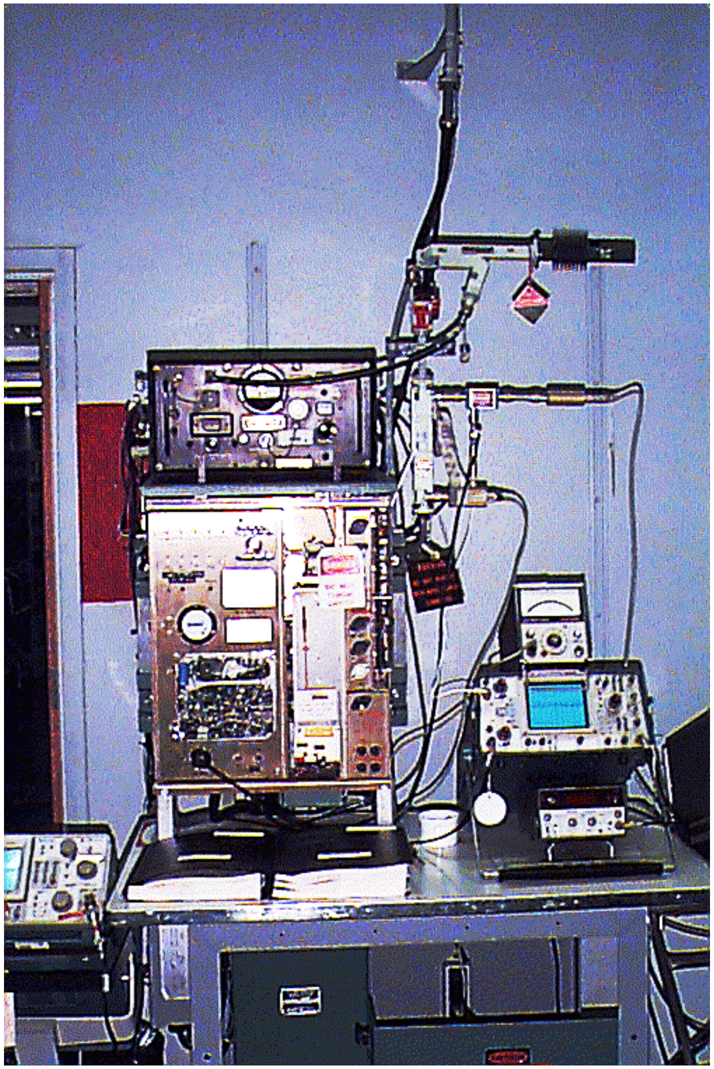
Secondary functions:

- Horizon and special search
- Self-test and diagnostics
- ECM operations

SPY-1 Radar Antenna



X-Band Search Radar (AN/SPS-64)



AN/SPS-64

X-band surface search and navigation.

- Three PRFs:
  3600, 1800, 900 Hz

- Range: 64 nm

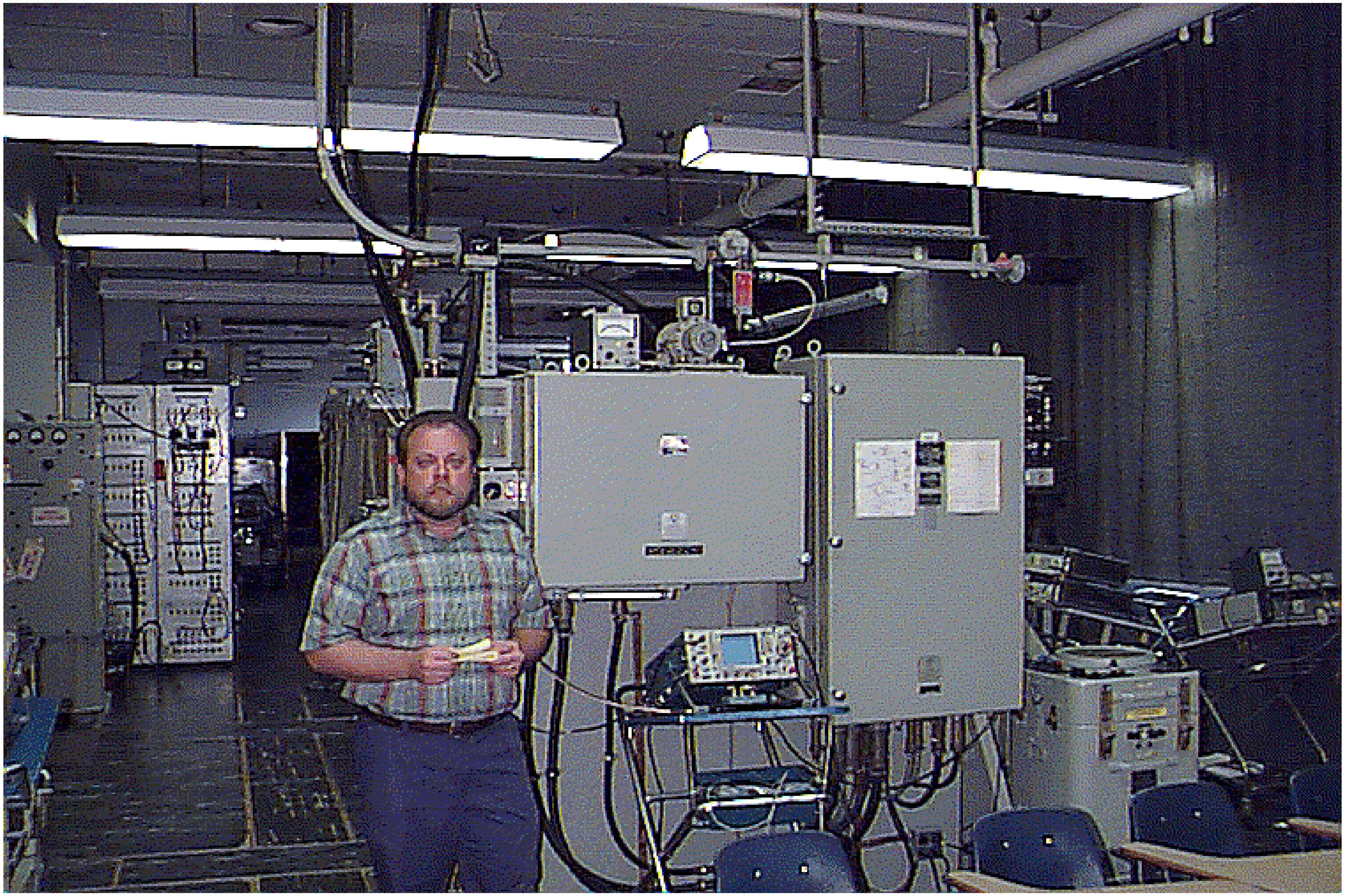
- Pulse widths:
  0.06ms, 0.5ms, 1.0ms

- Antenna
  Parabolic reflector
  Horiz HBPW: 1.2 degrees
  Vert HPBW: 20.7 degrees
  Gain: 28.5 dB
  SLL: -29 dB
  Polarization: horizontal

- Transmitter
  Frequency: 9.375 GHz
  Peak power: 20 kW

- Receiver
  IF gain: 120 dB
  MDS: - 98 dBm
  Noise figure: 10 dB
  IF frequency: 45 MHz
  IF bandwidth: 24, 4, 1 MHz
  False alarm rate: 1 per 5 minutes

C-Band Search Radar (AN/SPS-67)



AN/SPS-67

C-band surface search and navigation radar for detection of surface targets and low flying aircraft.

- Pulse width modes:
  1.0 ms, 0.25 ms, 0.1 ms

- Range in the three modes:
  300, 200, 75 yards

- Resolution in the three modes:
  200 yards, 190 ft., 75 ft.

- Transmitter
  Frequency: 9 to 9.5 GHz
  PRF: 1800 to 2200 Hz
  Pulse width: 0.22 to 0.3 ms

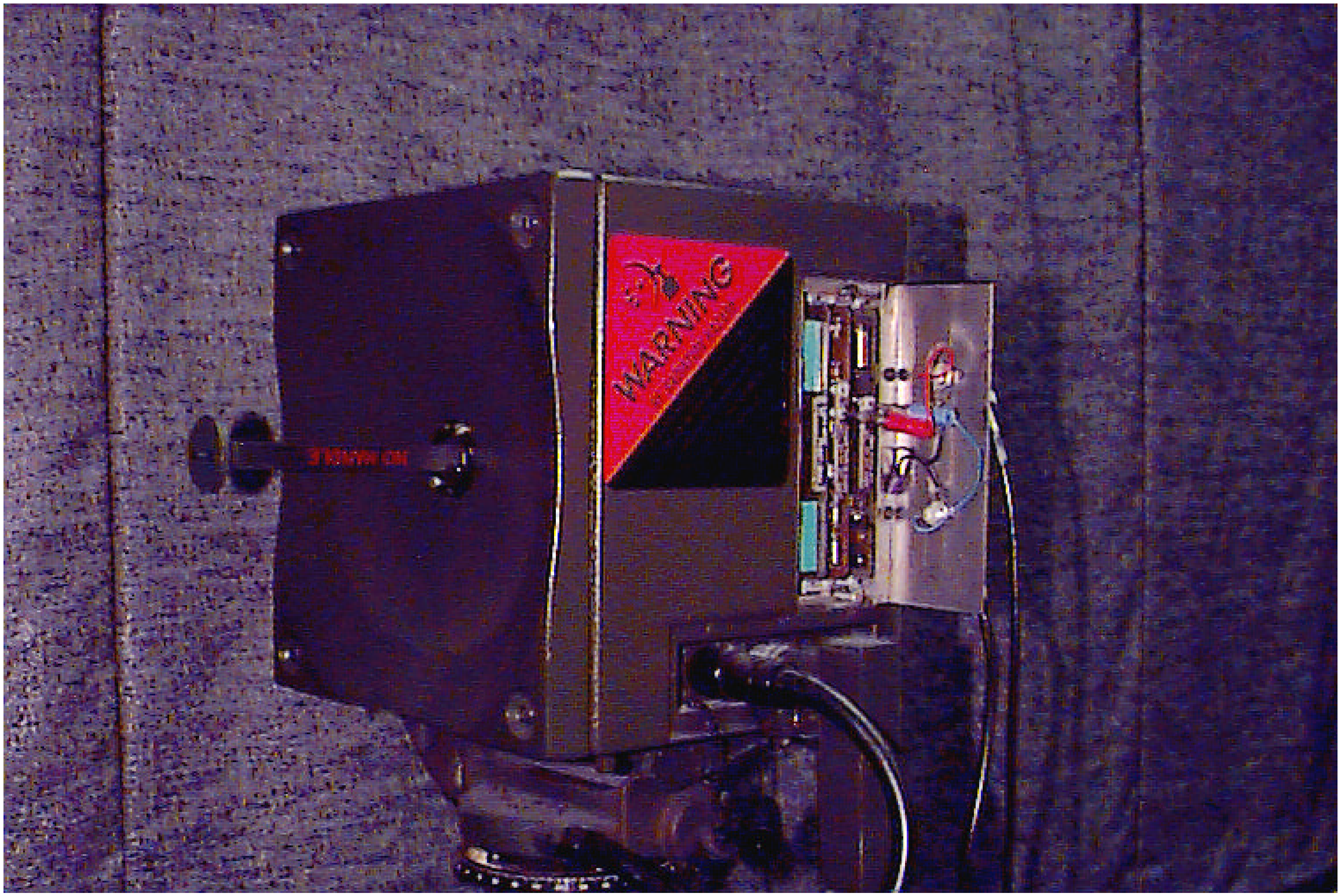
- Antenna
  Mesh reflector with dual band feed

- Transmitter frequency:
  5.45 to 5.825 GHz

- Receiver
  Noise figure: 10 dB
  MDS in the three modes:
  -102, -94, -94 dBm
  Logarithmic IF dynamic range
  90 dB or greater

- Display: PPI

Combat Surveillance Radar (AN/PPS-6)

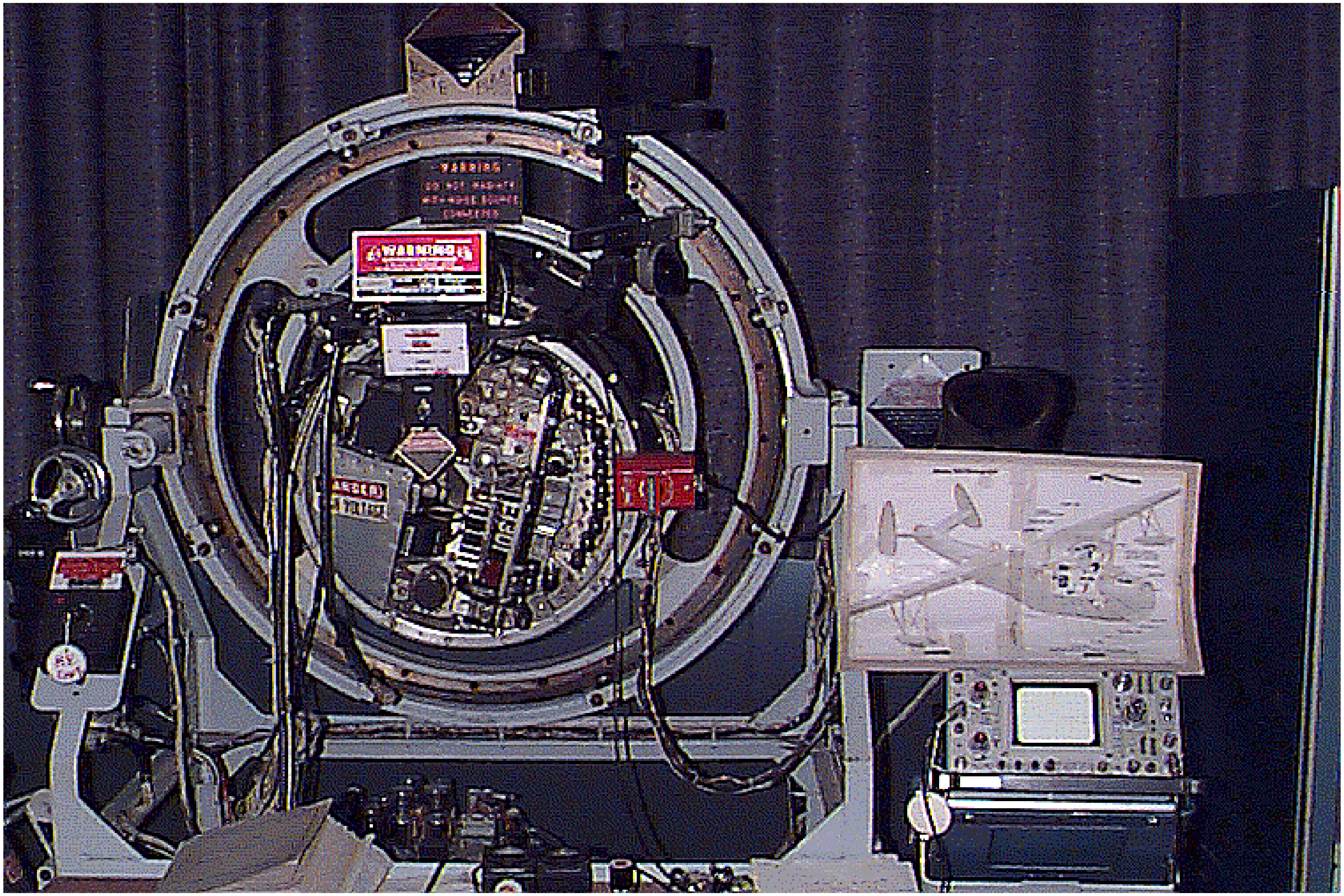


AN/PPS-6

Noncoherent pulse-doppler radar for combat surveillance. Detects moving terrestrial targets (1 to 35 mph) under varying conditions of terrain, visibility and weather conditions

- Range
  - Personnel ($s = 0.5$ sq. m):
    - 50 to 1500 m
  - Vehicles ($s = 10$ sq. m):
    - 50 to 3000 m
  - Accuracy: ±25 m
  - Resolution: 50 m
- Transmitter
  - Frequency: 9 to 9.5 GHz
  - PRF: 1800 to 2200 Hz
  - Pulse width: 0.22 to 0.3 ms
- Antenna
  - Size: 12 inch reflector
  - Gain: 24.5 dB
  - E-plane HPBW: 7 deg
  - H-plane HPBW: 8 deg
- Receiver
  - Type: superheterodyne
  - IF frequency: 30 ± 2 MHz
  - IF gain: 80 dB
  - IF bandwidth: 6.3 ± 0.6 MHz
  - MDS: -95 dBm
- Display
  - Headset (audible)
  - Test meter - visual indicator
  - Elevation indicator
  - Azimuth indicator

Early Air Surveillance Radar (AN/APS-31)



AN/APS-31

Early X-band surface search and navigation radar (about 1945).

- Pulse width modes:
  4.5 *m*s, 2.5*m*s, 0.5*m*s

- Range:
  5 to 200 nm

- PRFs in the three modes:
  200, 400, 800 Hz

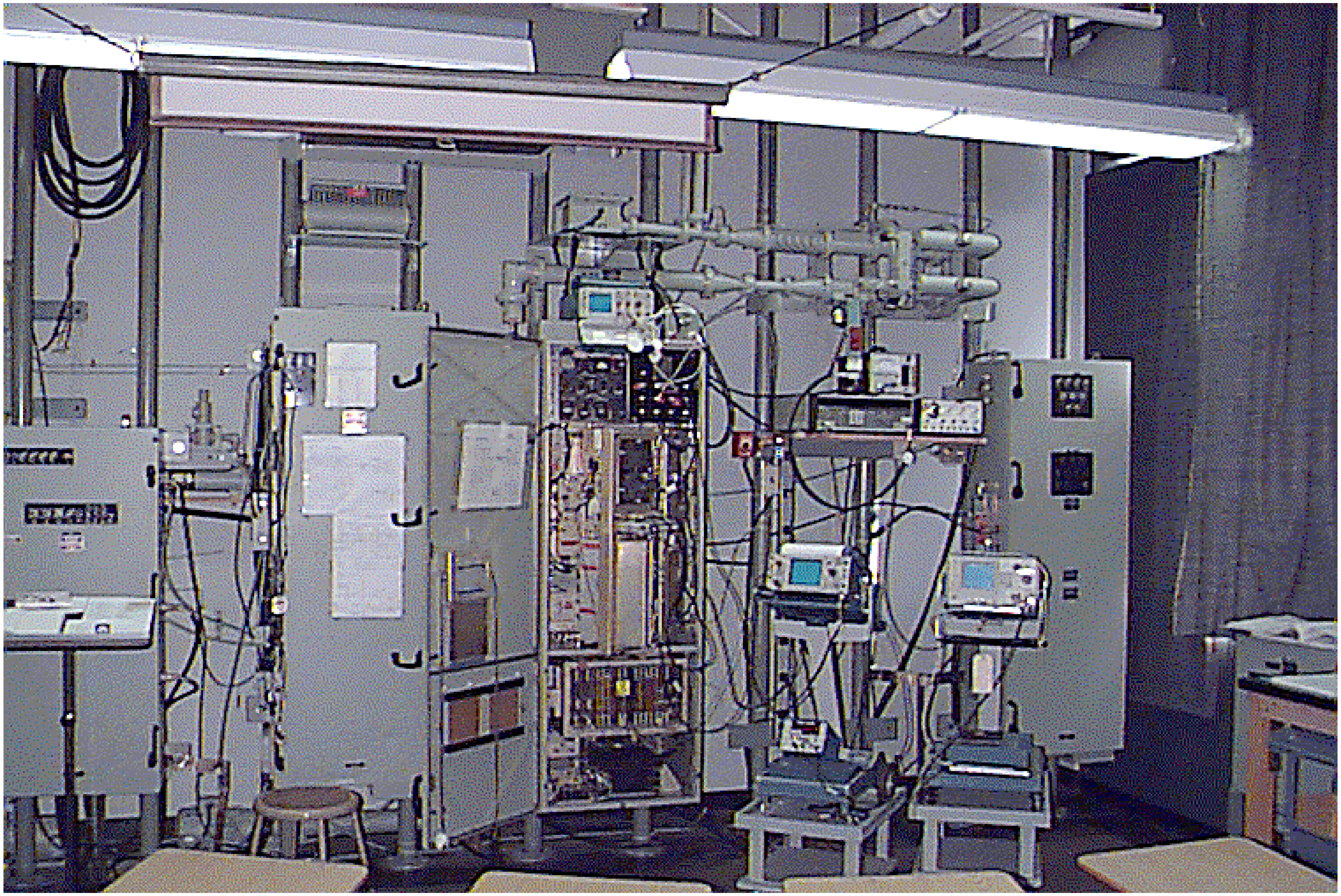
- Transmitter
  Peak power: 52 kw

- Antenna
  Parabolic reflector
  HBPW: 2 degrees
  Gain: 2500

- Transmitter frequency:
  9.375 GHz

- Receiver
  IF gain: 120 dB
  MDS in the three modes:
  -102, -94, -94 dBm
  Noise figure: 5.5 dB
  IF frequency: 60 MHz

AN/SPS-40



AN/SPS-40

UHF long range two-dimensional surface search radar. Operates in short and long range modes.

- Range
  - Maximum: 200 nm
  - Minimum: 2 nm

- Target RCS: 1 sq. m.

- Transmitter
  - Frequency: 402.5 to 447.5 MHz
  - Pulse width: 60ms
  - Peak power: 200 to 255 kw
  - Staggered PRF: 257 Hz (ave)
  - Non-staggered PRF: 300 Hz

- Antenna
  - Parabolic reflector
  - Gain: 21 dB
  - Horizontal SLL: 27 dB
  - Vertical SLL: 19 dB
  - HPBW (hor x vert): 11 by 19 degrees

- Receiver
  - 10 channels spaced 5 MHz
  - Noise figure: 4.2
  - IF frequency: 30 $\pm$2 MHz
  - PCR: 60:1
  - Correlation gain: 18 dB
  - MDS: -115 dBm
  - MTI improvement factor: 54 dB

Plan Position Indicator (PPI)

Radiometers (1)

All bodies at temperatures above absolute zero emit radiation due to thermal agitation of atoms and molecules. Radiometers are passive receiving systems that sense the emitted radiation.

A blackbody (BB) is an ideal body that absorbs all of the energy incident on it and radiates all of the energy that it absorbs. The radiation distribution as a function of wavelength (or frequency) is given by Planck's Law:

$$M_{\mathrm{BB}}(l) = \frac{2p\,h\,c^2}{l^5\left(e^{hc/(l\,k\mathrm{T})} - 1\right)}$$

where: $M_{\mathrm{BB}}(l) =$ spectral excitance of the blackbody in $\dfrac{\mathrm{W}}{\mathrm{m}^2 \cdot m\mathrm{m}}$

$h = 6.626 \times 10^{-34}$ J $\cdot$ s (Planck's constant)

$k = 1.3807 \times 10^{-23}$ J/K (Boltzman's constant)

$l =$ wavelength in mm

T = temperature of the body in degrees Kelvin

Radiometers (2)

The total radiance leaving the surface is

$$M_{\mathrm{BB}} = \int_0^{\infty} M_{\mathrm{BB}}(l)\,d\,l = s\,\mathrm{T}^4$$

where $s = 5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$ (Stefan-Boltzman constant).

The wavelength (or frequency) of maximum radiation for a BB of temperature T is given by Wien's displacement law

$$l_{\mathrm{max}}\mathrm{T} = 2897.6 \times 10^{-6}\ \ \mathrm{m \cdot K}$$

Only a few materials approach the characteristics of a blackbody. Most materials emit energy according to a scaled version of Planck's Law. These are called <u>gray bodies</u> and the scale factor is the <u>emissivity</u>

$$e(l) = \frac{M(l)}{M_{\mathrm{BB}}(l)}$$

Kirchhoff's Law states that at every wavelength the emissivity equals the absorptivity

$$e = a$$

Radiometers (3)

Since conservation of energy requires that

$$\text{absorbed} + \text{reflected} + \text{transmitted} = 1$$

it follows that good reflectors are poor emitters; good absorbers are good emitters.

Blackbody and gray body radiation is diffuse, that is constant with angle. The noise power radiated by a blackbody is $k\mathrm{T}B$ where B is the bandwidth of the detector. The power radiated by a gray body relative to that of a blackbody is

$$e = \frac{P_{\mathrm{GB}}}{k\mathrm{T}B} = \frac{\mathrm{T_B}}{\mathrm{T}}$$

where $\mathrm{T_B}$ is the brightness temperature. This difference in noise powers can be measured, and the emissivities determined. Emissivitiy can be used to infer the material characteristics.

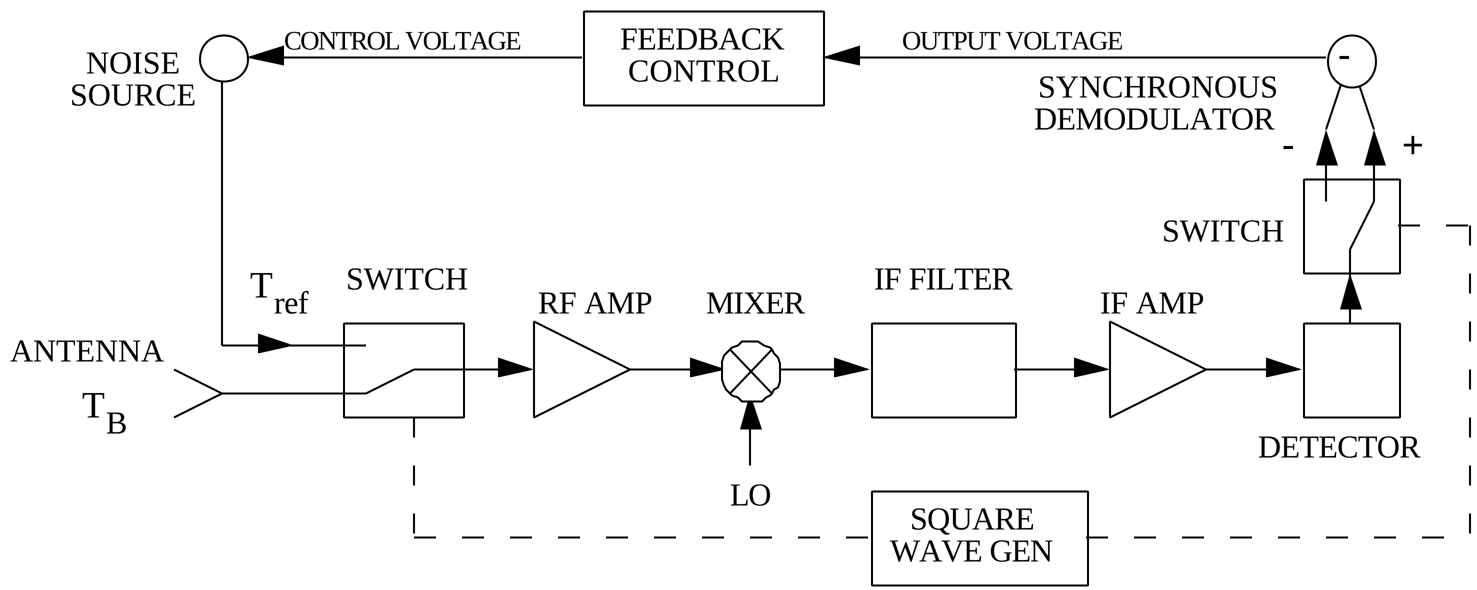
Radiometers (4)

Applications of radiometers:

Environmental:	Measure soil moisture Flood mapping Snow and ice cover mapping Ocean surface windspeed Atmospheric temperature and humidity profile
Military Applications:	Target detection and identification Surveillance Mapping
Astronomy:	Planetary mapping Solar emissions Mapping galactic objects Cosmological background radiation

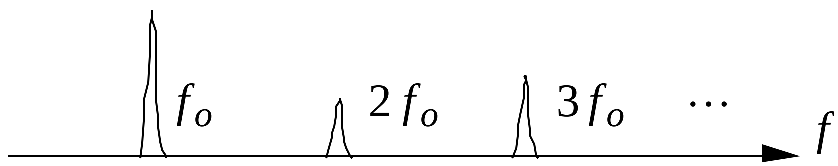
Radiometers (5)

Block diagram of the Dicke radiometer:



Harmonic Radar (1)

A harmonic radar transmits a frequency f_o (the fundamental) but receives a harmonic frequency ($f_o, 2f_o, 3f_o$, etc.). The harmonic frequencies are generated naturally by man-made objects with metal junctions. The harmonic can also be generated using a transponder circuit on the target.



Advantages:

1. Natural clutter sources are linear. They scatter waves at the same frequency as the incident wave. Therefore a target return at a harmonic is not obscured by clutter.
2. Man-made objects generate harmonic scattered fields. Odd numbered harmonics arise from metal junctions on the target. The third harmonic is the strongest.

Disadvantages:

1. Energy conversion from the fundamental to harmonics is very low. Higher conversion efficiencies can be obtained with cooperative targets using a nonlinear circuit device like a diode.
2. Dual frequency hardware required.
3. The received field varies as $P_r \propto 1/R^a$ where $a > 4$.

Harmonic Radar (2)

The <u>harmonic radar range equation</u> for the <u>third harmonic</u> is

$$P_r = \frac{(P_t G_t)^{\alpha} G_r \lambda_3^2 \sigma_h}{(4\pi)^{\alpha+2} R^{2\alpha+2}}$$

where:

$\alpha \approx 2.5$ is a nonlinearity parameter that determined experimentally
(it varies slightly from target to target)
P_t, G_t are transmit quantities at the fundamental frequency (f_o)
λ_3, G_r are receive quantities at the third harmonic frequency ($3f_o$)
σ_h is the harmonic scattering pseudo cross section
(typical values are -60 to -90 dB for $W_i \leq 1$ W/m^2)

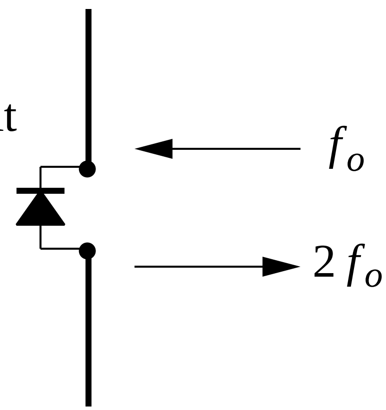
Using $\alpha \approx 2.5$ the received power varies as

$$P_r \propto 1/R^7$$

Therefore the detection ranges are very small, but foliage penetration is good for short ranges.

Harmonic Radar Tracking of Bees

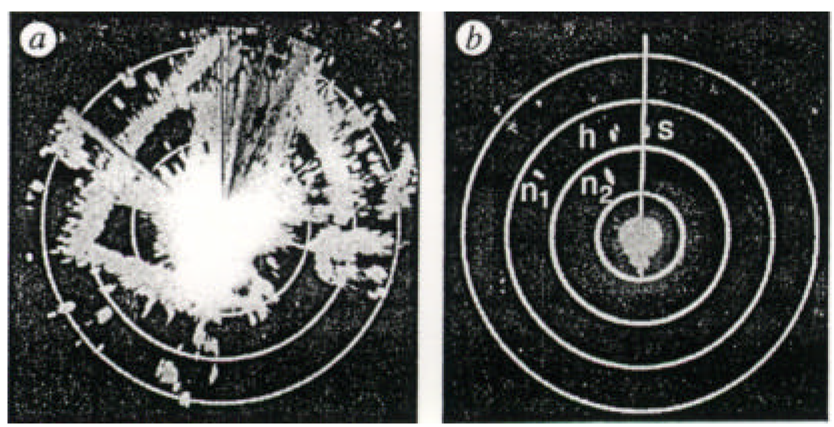
Dipole and diode circuit



Dipole and diode attached to a bee

(From *Nature*, Jan. 1996, p. 30)

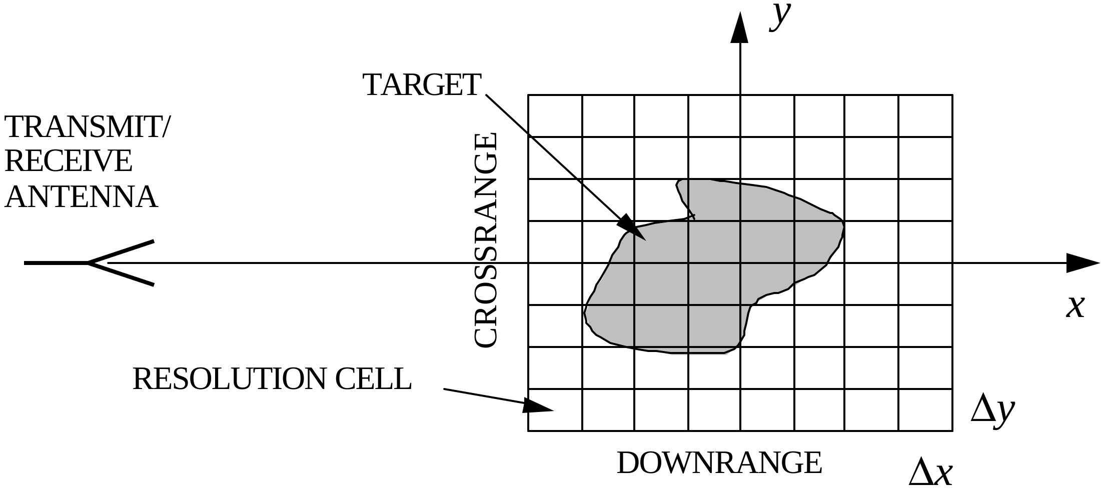
PPI traces for conventional and harmonic radars (l_o = 3.2 cm)



Synthetic Aperture Radar (SAR)

A scene (background plus targets) is imaged by plotting the received power as a function of ground coordinates. The resolution cell size is a picture element or pixel:

down range resolution (Δx) is determined by the pulse width
cross range resolution (Δy) is determined by the antenna beamwidth

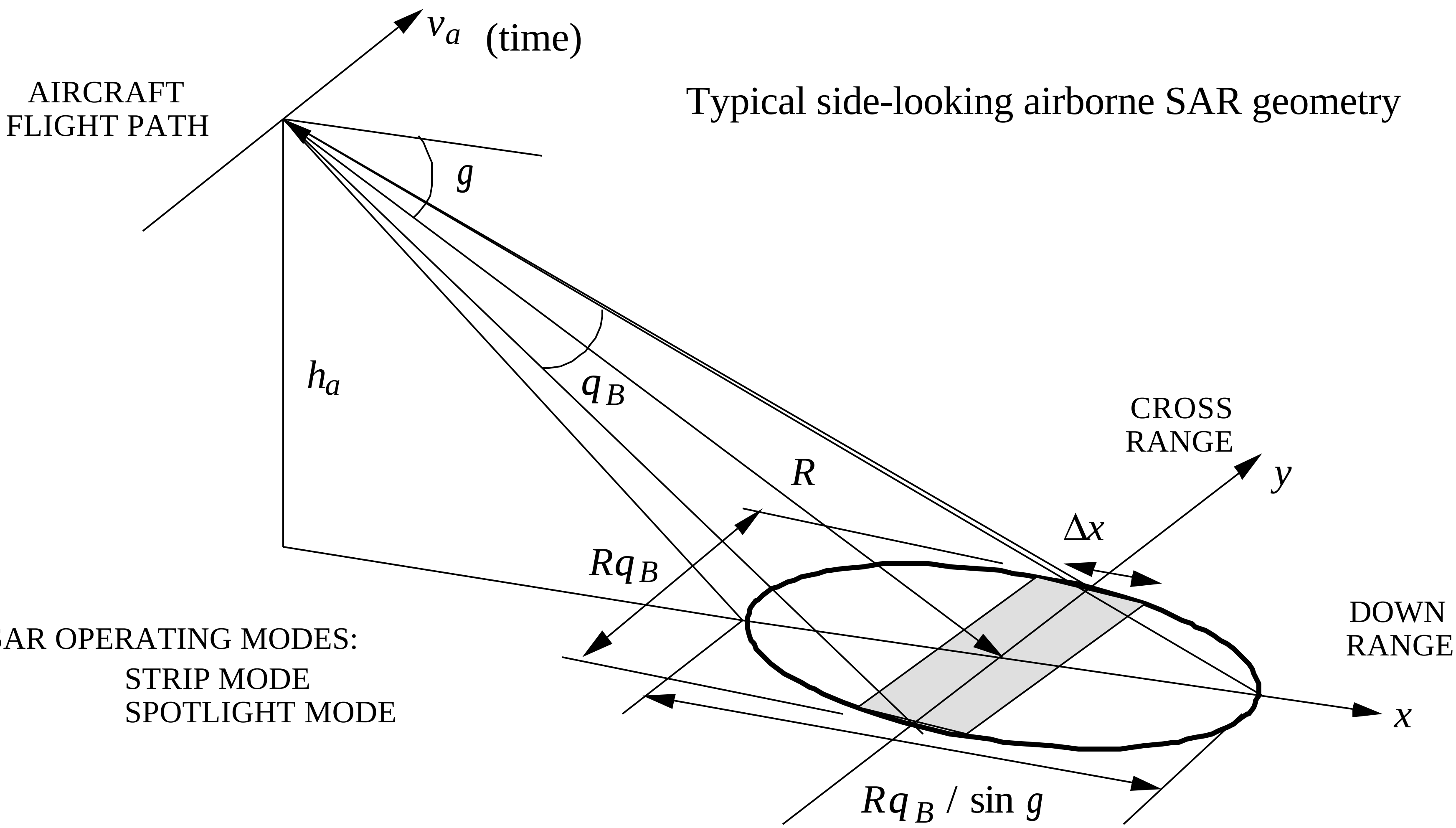


Actual grid is polar, but approaches a rectangular grid for large range.

Very narrow antenna beams are required for fine cross range resolution. The resulting antenna size is very large and may not be practical. Returns from a large antenna can be synthesized using the returns from a small antenna at sequential locations along a flight path. This is the basis of synthetic aperture radar (SAR).

SAR (2)

Typical side-looking airborne SAR geometry

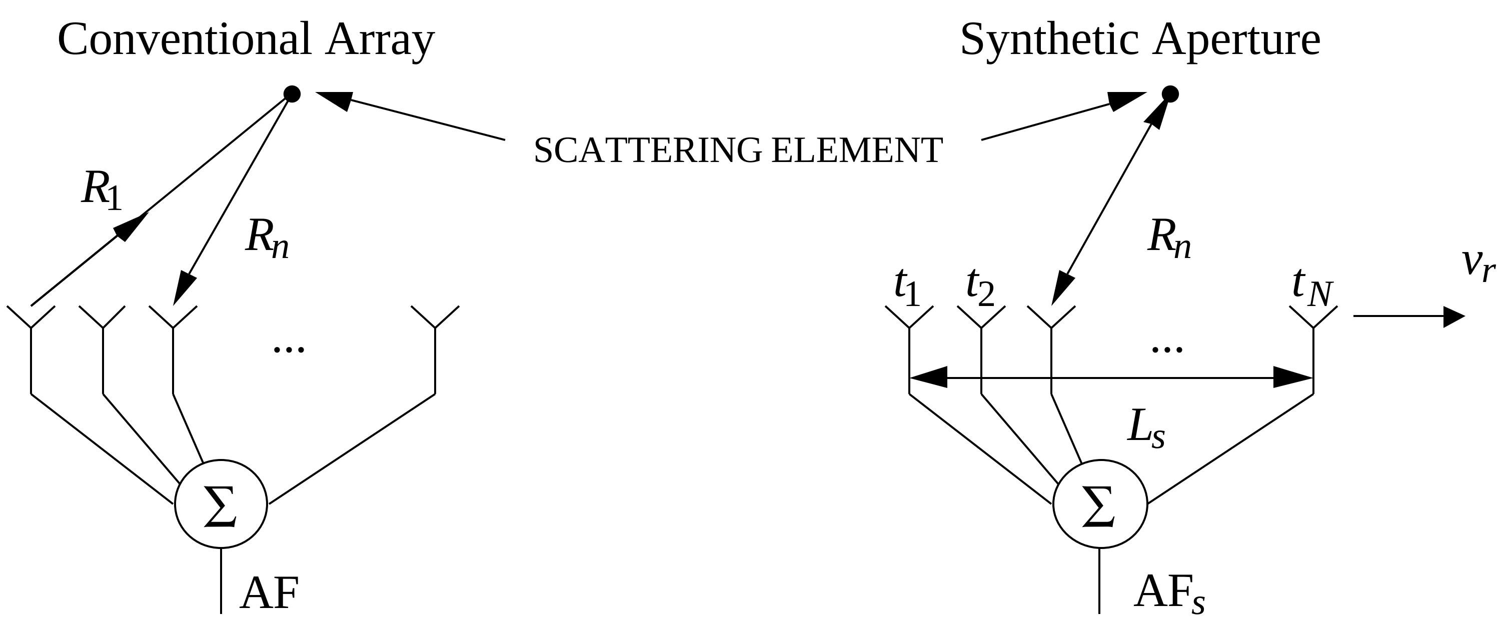


SAR OPERATING MODES:

STRIP MODE
SPOTLIGHT MODE

SAR (3)

Comparison of array factors for conventional and synthetic apertures:

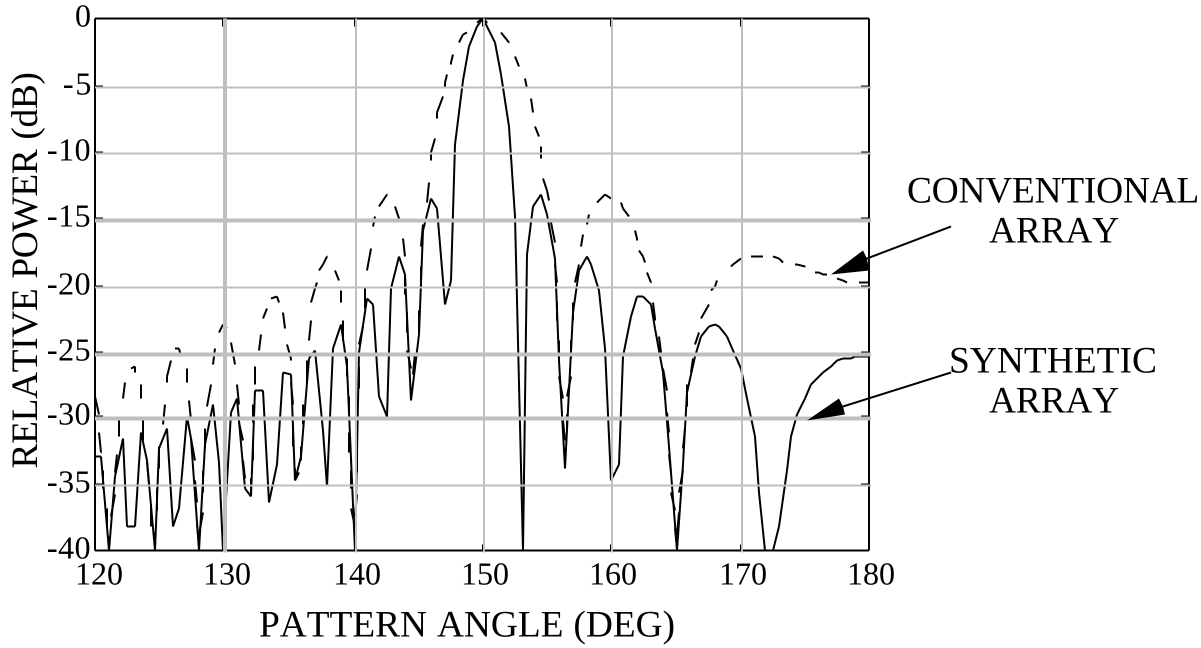


$$E_n = \sum_{m=1}^{N} e^{-jk(R_m + R_n)} \qquad\qquad E_n = e^{-jk(R_n + R_n)}$$

$$\mathrm{AF} = \sum_{n=1}^{N}\sum_{m=1}^{N} e^{-jk(R_m+R_n)} = \underbrace{\left(\sum_{m=1}^{N} e^{-jkR_m}\right)^2}_{\text{SQUARE OF SUM}} \qquad\qquad \mathrm{AF}_s = \underbrace{\sum_{m=1}^{N}\left(e^{-jkR_m}\right)^2}_{\text{SUM OF SQUARES}}$$

Comparison of Array Factors

Plot of array factors for conventional and synthetic apertures of the same length:

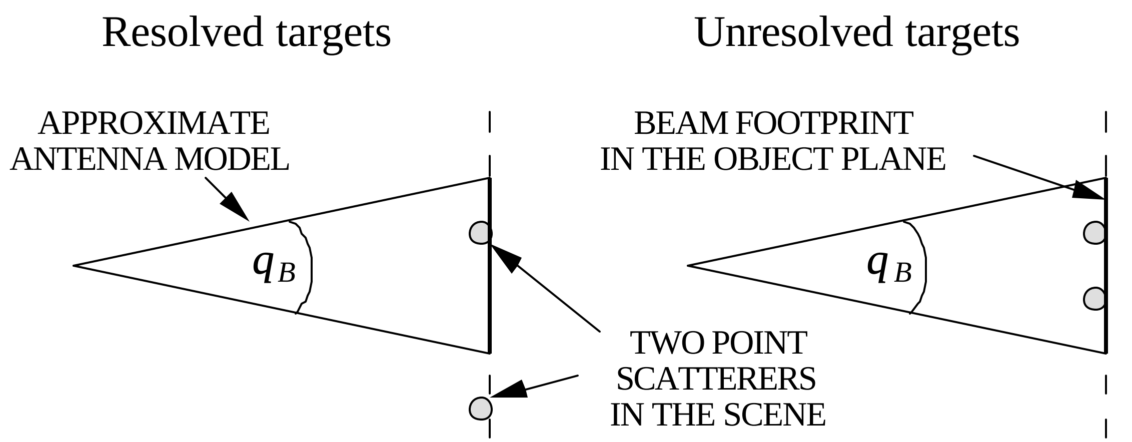


Beamwidth of the conventional array: $q_B \approx l / L$ where $L \approx Nd$ (d is the element spacing and N the number of array elements)

Beamwidth of the synthetic array: $q_B \approx l / (2L_s)$ where $L_s \approx t_{\text{obs}} v_a = d_{\text{obs}} N_s$ (t_{obs} is the observation time, N_s the number of samples, and d_{obs} the distance between samples)

Image Resolution

Two closely spaced targets are resolved if two distinct scattering sources can be distinguished.



For the conventional array the cross range resolution is

$$\Delta y = R\theta_B \approx R\lambda / L$$

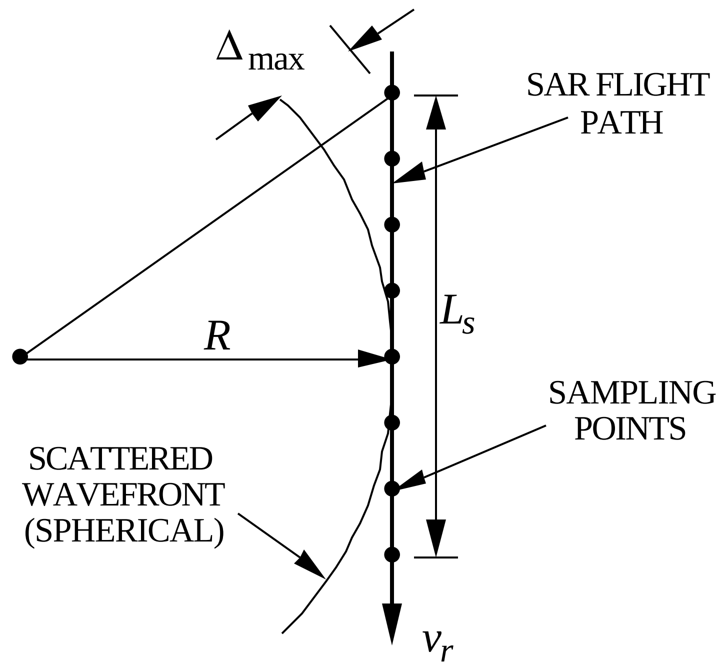
For the synthetic array the cross range resolution is

$$\Delta y = R\theta_B \approx R\lambda /(2L_s)$$

Note that the last result, which is based on AF_s, assumes that the wave scattered from a point source in the scene is a plane wave when sampled by the SAR.

Unfocused SAR (1)

If $\Delta_{\max}$ is too large then AF_s becomes distorted (the beam broadens). Therefore the maximum L_s is commonly determined by the condition $2k\Delta_{\max} \le p/2$



$$2k\left(\sqrt{R^2+(L_s/2)^2}-R\right)=2kR\left\{\sqrt{1+L_s^2/4R^2}-1\right\}\approx 2kR\{\underbrace{[1+L_s^2/(8R^2)]}_{\text{FIRST TWO TERMS OF BINOMIAL EXPANSION}}-1\}\le p/2$$

Unfocused SAR (2)

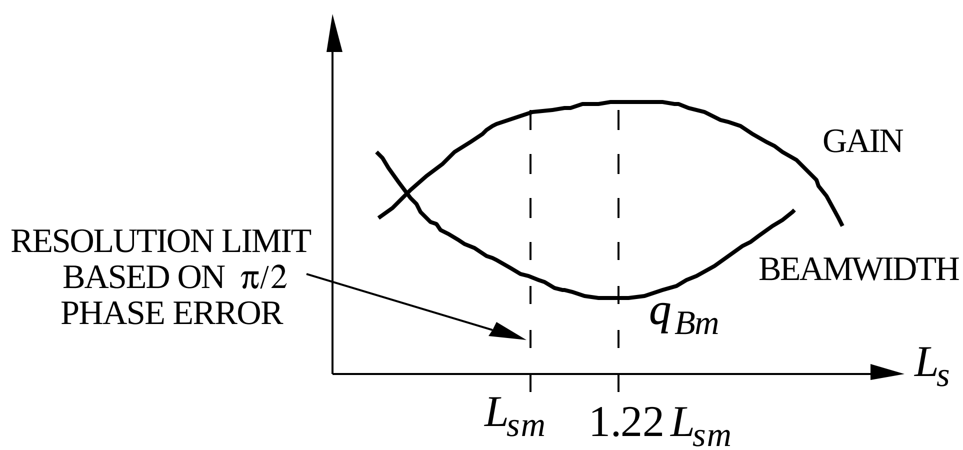
Solve for L_s and call this value L_{sm}

$$L_{sm} = \sqrt{Rl} \quad \Rightarrow \quad q_{Bm} = \frac{l}{2\sqrt{Rl}} = \frac{1}{2}\sqrt{\frac{l}{R}}$$

which gives a cross range resolution of

$$\Delta y_m = R q_{Bm} = \frac{1}{2}\sqrt{Rl}$$

This is the resolution limit for <u>unfocused SAR</u> (i.e., the phase error introduced by the spherical wavefront is not corrected). Note that the resolution does not depend on the actual antenna characteristics, only range and frequency. The actual optimum value is slightly different that L_{sm} depending on the antenna beamwidths and aperture distribution. A good estimate is $1.22 L_{sm}$.

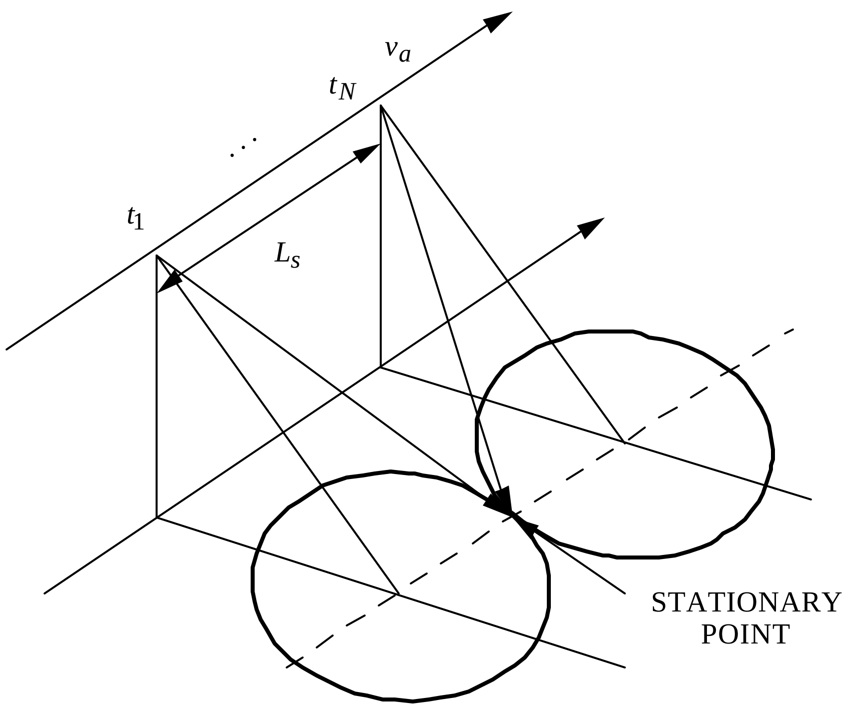


Focused SAR

Focused SAR corrects for the path difference in the signal processing. The result is an effective beamwidth determined by the total length of the synthetic array, $L_s = R l / L$. The corresponding resolution is

$$\Delta y = R q_B = R\left(\frac{l}{2L_s}\right) = \frac{L}{2}$$

which is independent of R and l, and depends only on the actual size of the antenna.



The smaller the antenna used by the radar, the better the resolution because:

1. a wide beam keeps each scatterer in view longer, and
2. focusing (i.e., adding corrections) removes the range dependence.

The synthetic aperture length L_s is limited by the time that a point scatterer remains in the beam footprint.

Example

SAR is used to image clutter

$$B = 20\,\text{MHz}, \quad \theta_s = 20^\circ \; (\psi = 70^\circ), \quad h_a = 800\ \text{km}, \quad \lambda = 23\,\text{cm}, \quad L = 12\ \text{m}$$

The down range resolution is

$$\Delta x = \frac{c\tau}{2\cos\psi} = \frac{(3\times 10^8)\overbrace{(1/20\times 10^6)}^{\tau = 1/B}}{2\cos(70^\circ)} = 22\,\text{m}$$

The cross range resolution for a conventional antenna is

$$\Delta y = R\theta_B = \frac{h_a}{\cos(\theta_s)}\frac{\lambda}{L} = \frac{800\times 10^3}{\cos(20^\circ)}\frac{0.023}{12} = 1.63\,\text{km}$$

For an unfocused SAR ($\pi/2$ condition)

$$\Delta y_m = \frac{\sqrt{R\lambda}}{2} = \frac{\sqrt{(0.023)800\times 10^3/\cos(20^\circ)}}{2} = 70\,\text{m}$$

For a focused SAR

$$\Delta y = L/2 = 6\,\text{m}$$

Cross Range Processing (1)

The cross range coordinate can be obtained in several ways. Three common approaches are:

1. Side-by-side (sequential) processing: As each new time sample is collected, the oldest time sample is discarded. A new beam footprint is generated that is slightly translated in the along-track direction. A small footprint must be generated to resolve closely spaced scatterers. A massive amount of data must be processed for each time step. Cross range resolution is limited. Early SARs used this method.

The properties of the doppler shift of a point on the ground as a function of time can be used to resolve scatterers in the cross range coordinate:

2. Chirp structure of the return: The return from a scatterer on the ground has a chirp structure. A matched filter can be designed to exploit the chirp structure and improve the resolution across the beam footprint.

3. Doppler processing of the return: The “doppler history” of individual points on the ground can be used to resolve scatterers with doppler filter banks.

Cross Range Processing (2)

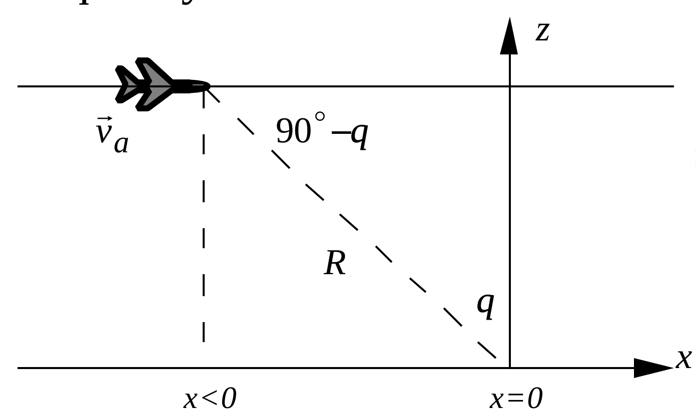
Consider an airborne SAR illuminating a stationary point target on the ground. For the geometry shown, the doppler as a function of time is given by (note: $q > 0 \rightarrow x < 0$)

$$f_d = \frac{2v_a \sin q}{l} = \frac{2v_a (x/R)}{l} = \frac{-2v_a^2 t}{lR}$$

This is a chirp signal with $\frac{m}{2} = \frac{-4p v_a^2}{lR}$. A chirp filter can be used on receive to resolve scatterers in cross range. If the radar is in motion, then there will be a timing error (i.e., range error) in the matched filter response due to the radar's velocity. The radar motion can be compensated for by subtracting out the known doppler (using the estimated ground speed). However, if the point target is in motion, its doppler will cause the target to be displaced in the image from its actual location. In a SAR image this results in cars not on roads, ships displaced from wakes, and so forth.

$$\Delta t = \frac{w_d}{m/2} = \frac{lR}{2v_a^2} f_d$$

Note that if motion compensation is used, then f_d will be the uncompensated doppler frequency.



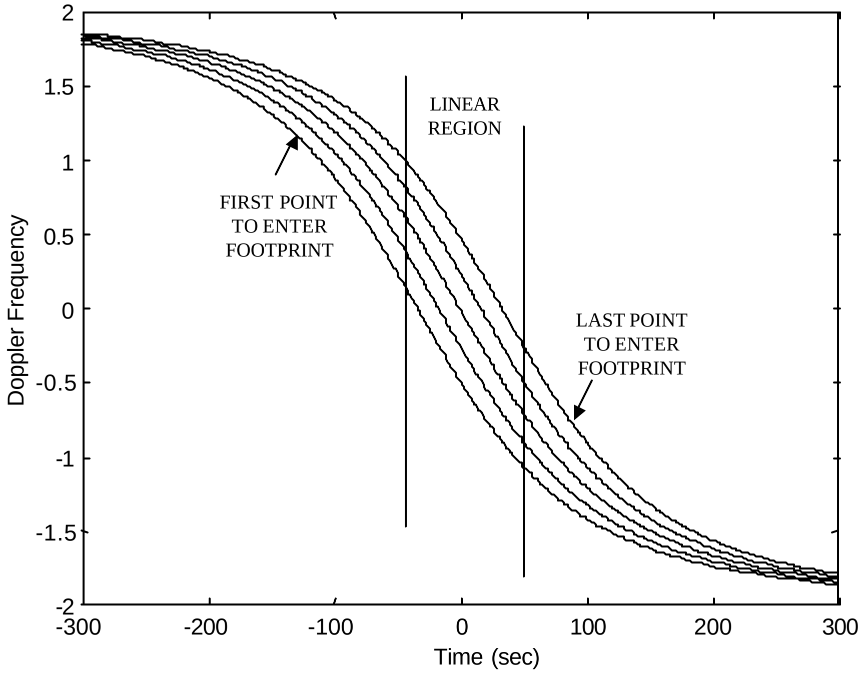
$$\sin q = \frac{x}{R}$$

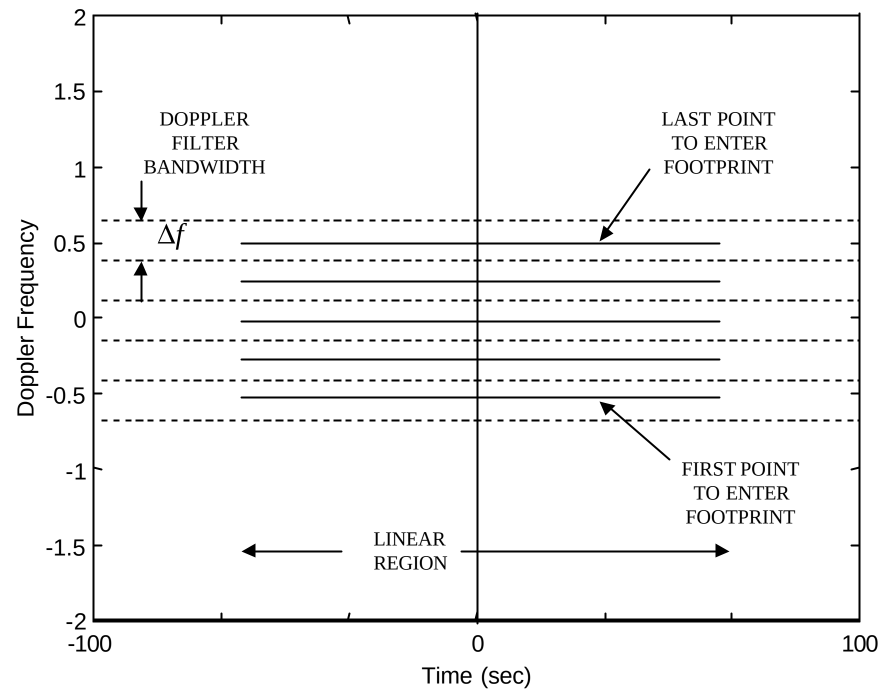
$$x = v_a t$$

Cross Range Processing (3)

The doppler shift of a stationary point on the ground has a unique time history as the beam footprint passes by, as shown in the example below for four scatterers. If the processing time is limited to the linear region, the curves can be "de-ramped" (slope removed) and Fourier transformed to obtain the frequency components.

$$h_a = 20 \text{ km}, \ l = 1 \text{ m}, g = 30^\circ, v_a = 300 \text{ m/s}$$

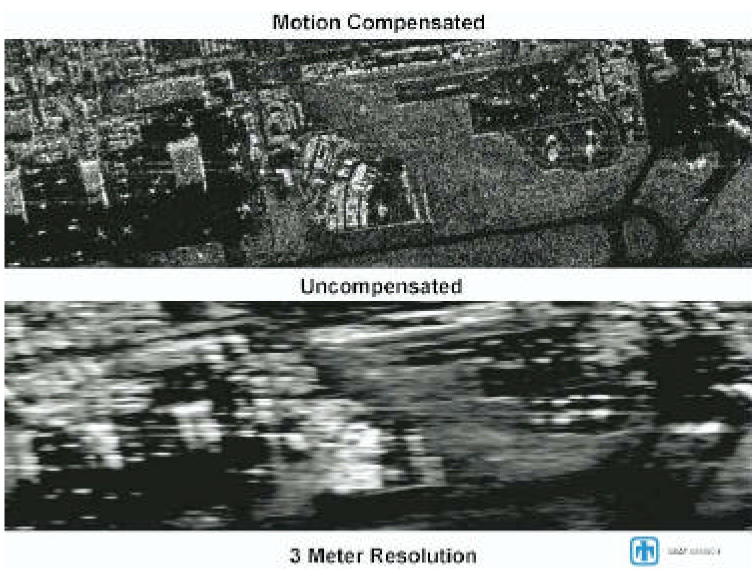


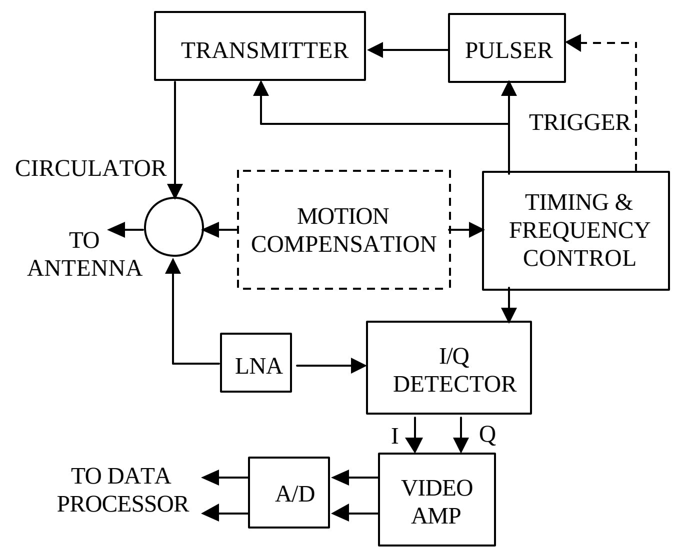


Motion Compensation

The radar platform has motion variations that can cause blurring and displacement of objects in the image. Motion compensation involves estimating the displacement from the along track direction and deviations from a constant velocity and correcting for them in the processing. Several levels of correction may be required:

- The antenna may have to be stabilized or re-steered
- Timing must be re-adjusted if the radar travels off of the ideal flight line by more than the range resolution
- If phase information is used in processing, then phase errors due to cross track and vertical random motion must be held to less than l /10





Radar Mapping

Key features:

1. Radar provides its own illumination; operates in all conditions
2. Large area coverage in a short time
3. Surface features obtained in spite of vegetation and clouds
4. Operates at relatively low grazing angles
5. Images a plan view

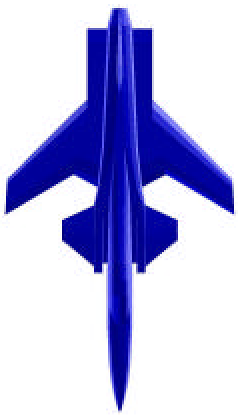
Resolution requirements:

FEATURES	CELL SIZE
Coastlines, large cities, outlines of mountains	500 feet
Major highways, variations in fields	60 – 100 feet
Road map (city streets, large buildings, airfields	30 – 50 feet
Houses, small buildings	5 – 10 feet
Vehicles and aircraft	1 – 5 feet

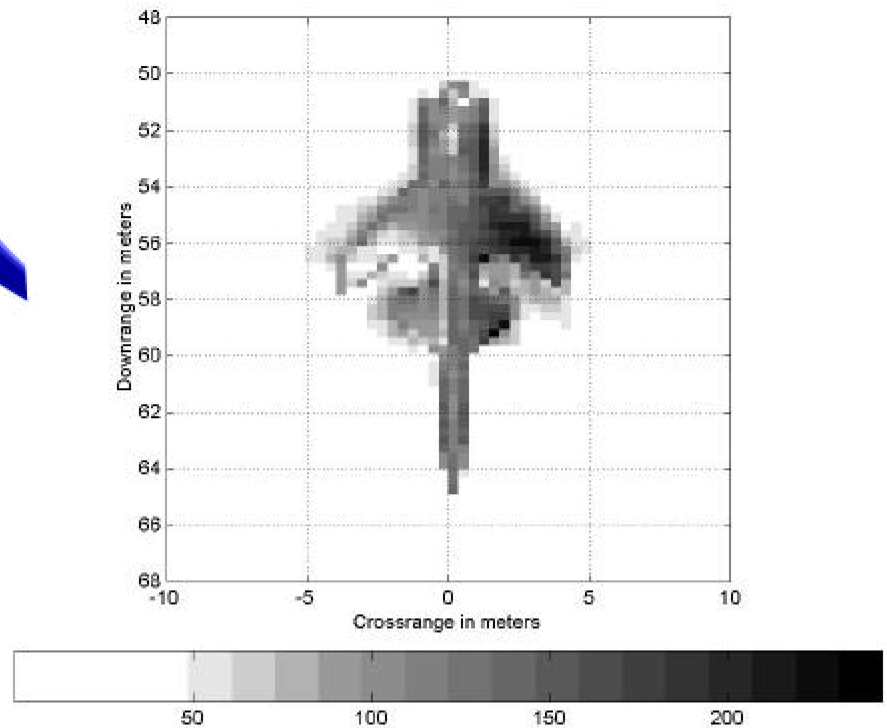
SAR Image

Echo intensity plotted versus down range and cross range coordinates

X-29
TARGET



STEPPED FREQUENCY IMAGE



SAR Range Equation

Start with standard RRE:

$$SNR = \frac{P_t A_e^2 \sigma\, n_B}{4\pi \lambda^2 k \mathrm{T}_s B_n R^4}$$

Substitute the following:

$$t_{\mathrm{obs}} = t_{\mathrm{ot}} = \frac{n_B}{f_p} = \frac{L_s}{v_a} \quad \Rightarrow \quad n_B = \frac{L_s f_p}{v_a}$$

$$P_t = \frac{P_{\mathrm{av}}}{\tau\ f_p}, \quad \tau B_n \approx 1 \text{ and } \quad \sigma = \sigma^o A_c = \sigma^o \Delta x\, \Delta y$$

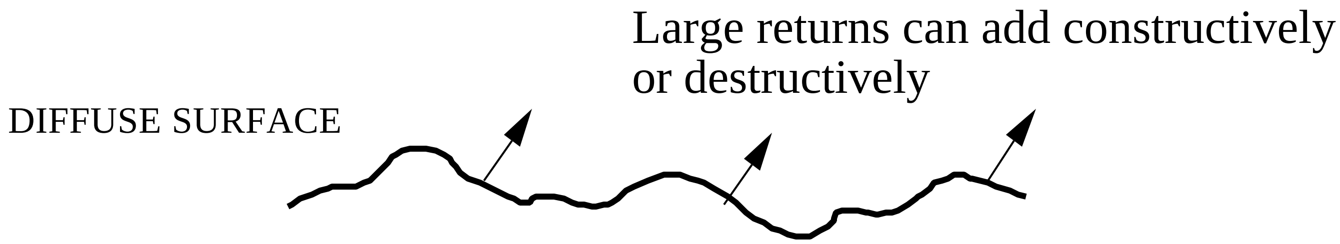
to obtain

$$SNR = \frac{P_{\mathrm{av}} A_e^2 \sigma^o \Delta x \Delta y (L_s f_p / v_a)}{4\pi\ \lambda^2 k \mathrm{T}_s B_n R^4 \tau\ f_p} = \frac{P_{\mathrm{av}} A_e^2 \sigma^o \Delta x \Delta y\ t_{\mathrm{obs}}}{4\pi\ \lambda^2 k \mathrm{T}_s R^4}$$

For pulse width limited illumination and focused SAR, $\Delta x = \dfrac{c\tau}{2\cos\gamma}$ and $\Delta y = \dfrac{L}{2}$

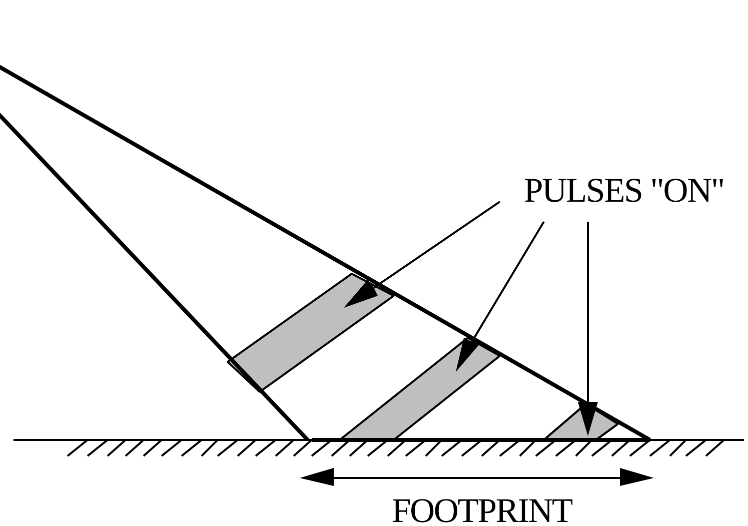
SAR Problems (1)

1. Speckle – occurs when returns from diffuse surfaces are added coherently.



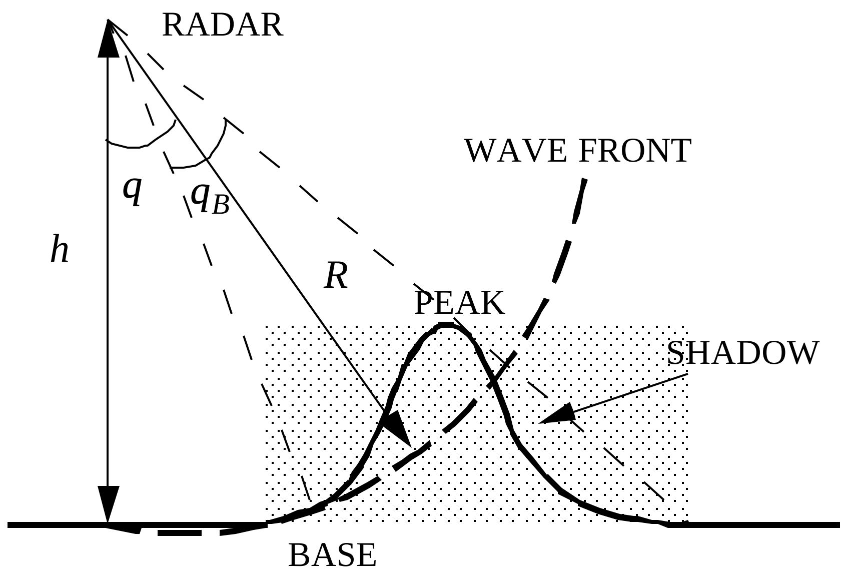
2. Motion effects – for satellite based SAR, earth's rotation can be important.
3. Range curvature – the illuminated strip can be curved rather than straight.
4. Changing atmospheric conditions – rain, moisture, dust, etc.

5. Ambiguities if more than one pulse in a surface swath



SAR Problems (2)

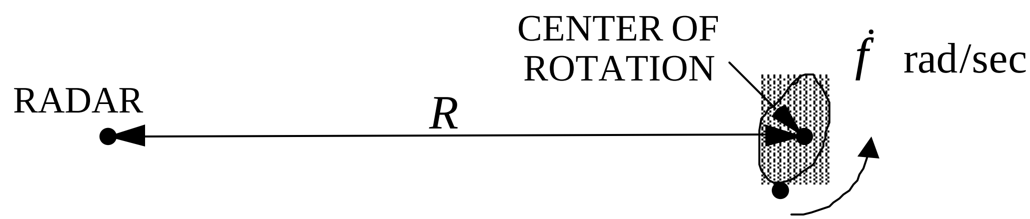
6. Layover – occurs when an object's top is in a closer range bin than the object's bottom. The object appears to be "laid over" on its side in the image.



7. Shadows – appear dark in the image due to lack of illumination of the shadowed area.
8. Multipath – can lead to multiple copies of the same object in the image, or displacement of object in the image.

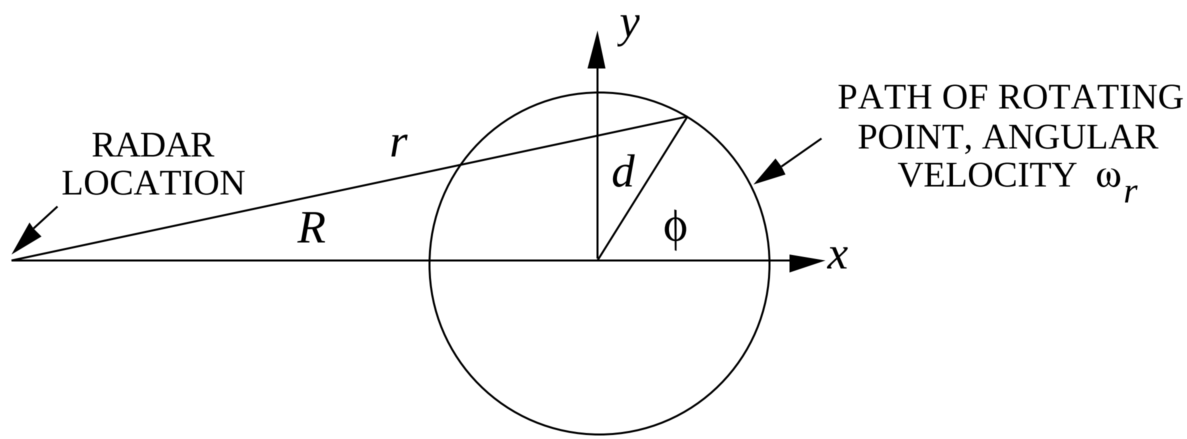
Inverse Synthetic Aperture Radar (ISAR)

Generally, ISAR refers to the case where the cross range information is obtained from target dopper. Consider a rotating target at range *R*.



A typical point on the target rotates a radius *d* about the center of rotation. Using the law of cosines

$$r^2 = R^2 + d^2 - 2dR\cos(\pi - \phi) \underset{R>>d}{\Rightarrow} r \approx R\sqrt{1 + \frac{2d\cos\phi}{R}} \approx R + d\cos\phi$$



ISAR (2)

The scattered field from the rotating point is

$$E_s \propto e^{jwt} e^{-j2kr} = \underbrace{e^{jw\,t}}_{\text{CARRIER}} \cdot \underbrace{e^{-j2kR}}_{\substack{\text{DELAY} \\ \text{TO CENTER}}} \cdot \underbrace{e^{-j2kd\cos f}}_{\substack{\text{DOPPLER SHIFT} \\ \text{FROM ROTATION}}}$$

Doppler frequency

$$w_d = 2p\, f_d = \frac{d}{dt}\left(-2kd\cos(\dot{f}\,t)\right) = \frac{2\dot{f}d}{l}\sin(\dot{f}\,t)$$

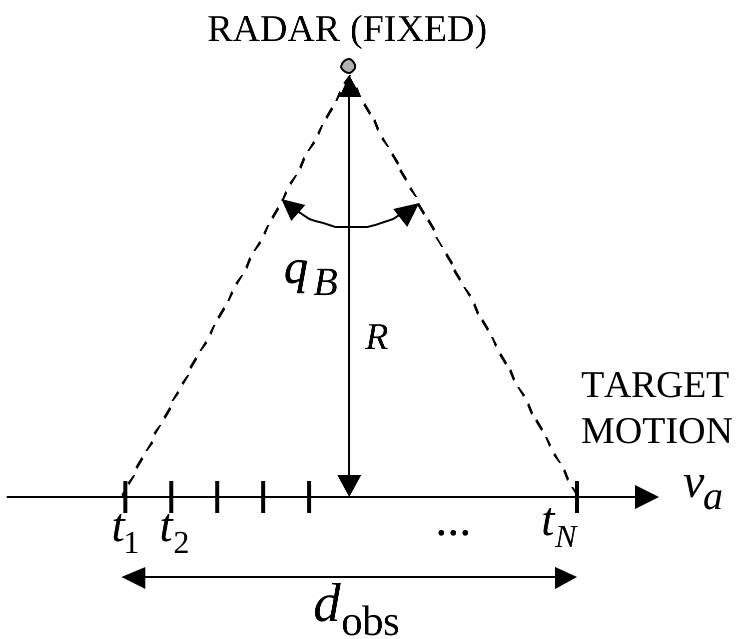
and the cross range coordinate

$$f_d = \frac{2\dot{f}}{l}\underbrace{d\sin f}_{=y} \quad \Rightarrow \quad y = \frac{l\, f_d}{2\dot{f}}$$

which can be found because $\dot{f}$ is known. A similar situation applies if the target is stationary and the radar circles the target.

ISAR (3)

ISAR has been applied to targets with linear motion. The geometry is similar to that of the airborne SAR on a straight flight path, but the locations of the radar and target are reversed. Over the observation time, T_{obs}, a synthetic beam, q_B, is formed. The array factor is the same as for airborne SAR.



- The cross range resolution at range R is

$$\Delta y = R q_B$$

- The observation distance is used to determine the beamwidth (rather than the synthetic length)

$$q_B \approx l /(2 d_{\text{obs}})$$

- Cross range resolution can be improved by increasing the observation (integration) time

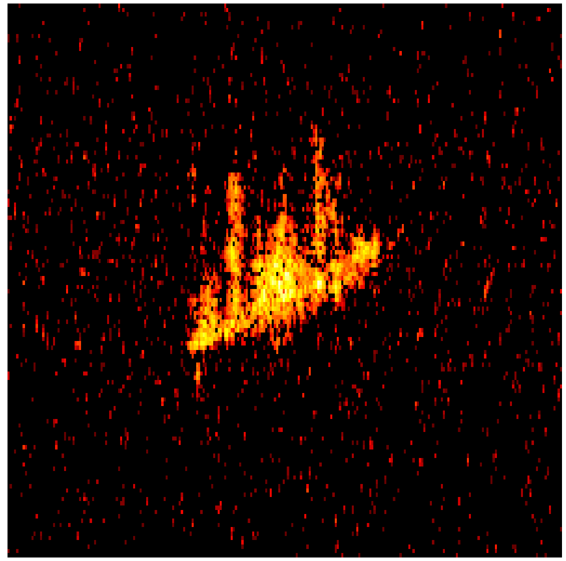
$$\Delta y = R l /(2 v_a T_{\text{obs}})$$

- The radar does not have control of the target's flight characteristics.

ISAR (4)

USS Crocket

ISAR Image



(From NRL web site: http://radar-www.nrl.navy.mil/Areas/ISAR/)

HF Radars (1)

- Radars that operate in the high frequency (HF) band are also called over the horizon (OTH) radars. Advantages:
  1. Long range target detection
  2. Low altitude target detection
  3. Operates in target scattering resonance region (i.e., detection of low observable targets)
  4. Low probability of intercept

- Major applications: Protection of land mass from attack (ships and aircraft)

- Atmospheric propagation mechanisms:
  1. Sky wave: the interaction of HF waves and the Earth's ionosphere, which is the upper atmosphere (heights ≥ 80 km)
  2. Ground wave: over the horizon diffraction

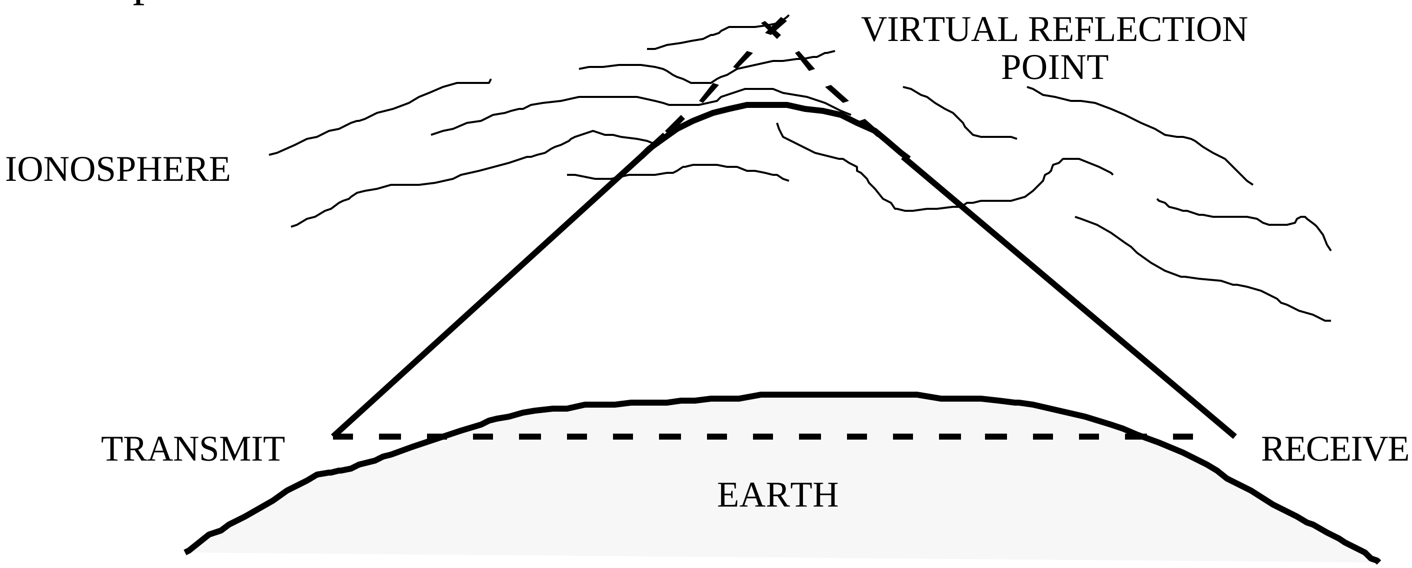
- Comparison of operational ranges:

Conventional microwave:	200 km
HF ground wave:	200 to 400km
HF sky wave:	1000 to 4000 km

HF Radars (2)

Atmospheric propagation issues:

1. The properties of the ionosphere are constantly changing with:
   time of day, time of year, solar activity
2. Ionospheric reflections appear to originate at multiple reflective layers at different heights. This often causes <u>multipath fading.</u>
3. Ionospheric reflections are strongly dependent on frequency and antenna "launch" angle. A wide range of frequencies must be used.
4. Efficient operation requires knowledge of the current state of the ionosphere.



HF Radar (3)

Other HF radar issues:

External noise sources are greater than internally generated noise. They include

1. atmospheric (lightning)
2. cosmic
3. man made (radio, ignition, etc.)

The ionosphere is dispersive and hence there are limits on the information bandwidth.

Clutter is strong. Sources include the earth, auroral ionization and meteor ionization.

Ionospheric reflection allows a specific area of the earth's surface to be illuminated by only a limited band of frequencies.

Multipath fading can be severe. Ionospheric paths have high attenuation. Conclusion: the sky wave path can be made reliable if one is willing to pay the cost.

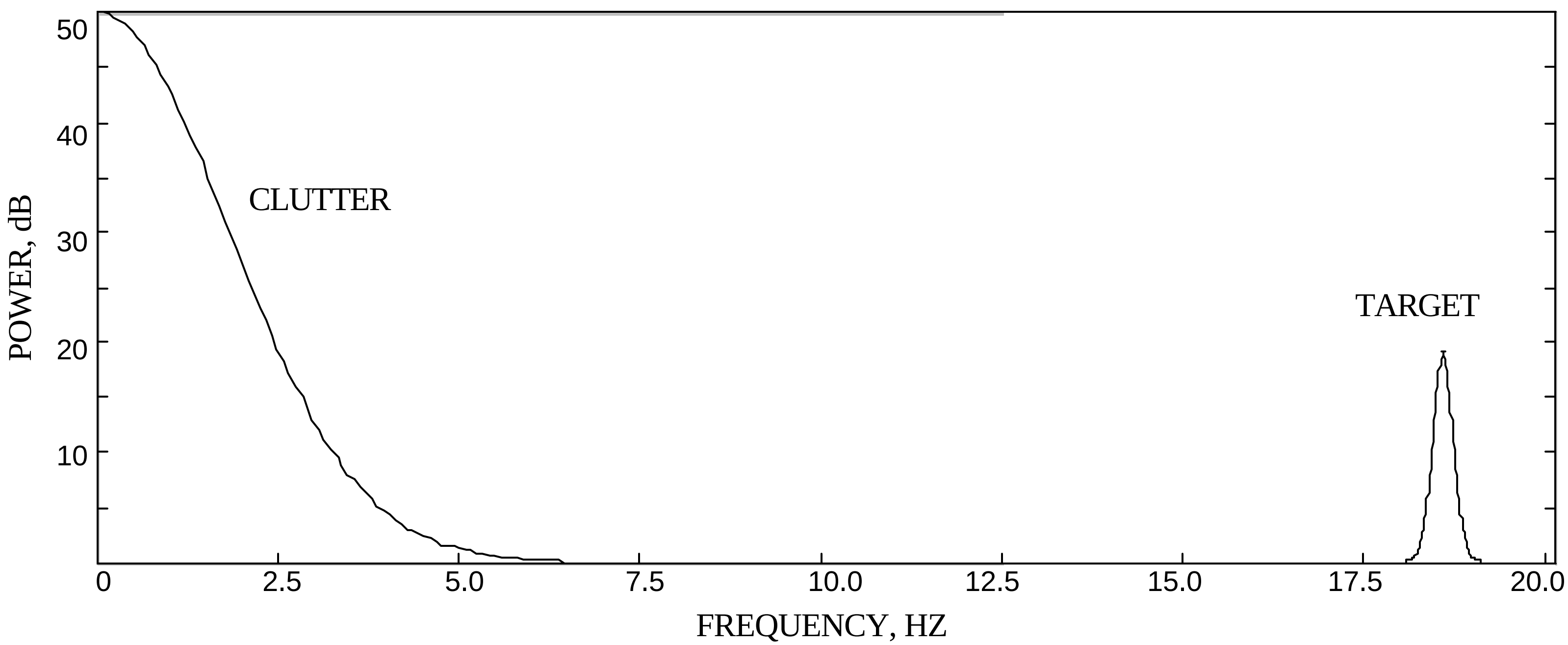
Typical HF OTH Radar Parameters

PARAMETER	*TYPICAL VALUES*
range	1000 to 4000 km
range resolution	2 km to 40 km
range accuracy	2 km to 20 km
angle resolution	0.5 to several degrees (ionosphere limits angle resolution to some fraction of a degree)
angle accuracy	approximately 12 km at 1500 km
Doppler resolution	as little as 0.1 Hz (about 1.5 knots)
operating frequency	4 MHz to 40 MHz, electronically tuned
peak output power	20 kw to 1 Mw
PRF	CW to 50 Hz
pulse width	10 ms to 200 ms
antenna gains	15 dBi to 30 dBi (transmit and receive antennas are usually different and multiple beams are used on receive
azimuth (horizontal) beamwidth	0.5 to 20 degrees (often narrow receive, wide transmit)
elevation (vertical) beamwidth	10 to 60 degrees (vertical apertures is costly)
azimuth/elevation beam steering	20 to 150 degrees/0 to 30 degrees
dwell time	ten seconds or more

Typical HF Clutter and Target Spectrum

Example:

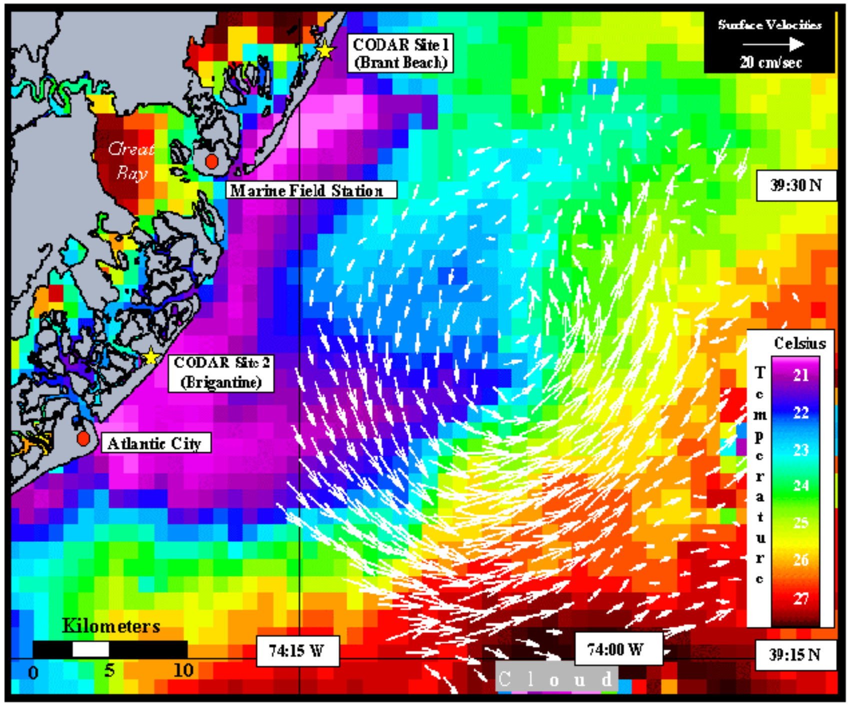
Target Speed (relative velocity)	Doppler Shift (Hz)	
	at 3 MHz	at 30 MHz
9 m/s (20 mph)	0.18	1.8
90 m/s (200 mph)	1.8	18



HF Coastal Radar (CODAR)

Characteristic	Value
Operating frequency	27.65 MHz
Transmitted power	30 W
Working range (35 PSU salinity)	up to 50 km
Length of sea surface wave (Bragg)	5.42 m
Depth over which current is averaged	~0.5 m
Range resolution	0.3 km, 0.6 km, 1.2 km
Azimuthal resolution (Direction Finding)	1 degree
Azimuthal resolution (Beam Forming)	+/-3 degrees
Integration time	9 minutes, 18 minutes
Accuracy of radial component	1...2~cm/s
Accuracy of current field	1...5~cm/s

Surface current map



University of Hamburg WERA HF radar

Relocatable Over the Horizon Radar (ROTHR)

- The Navy radar was originally designed for wide area ocean surveillance for fleet defense
- Since 1989 it has been used by the Coast Guard and Customs for the detection of drug running
- Operates in the 2 to 30 MHz frequency band
- Vertical and down range backscatter sounders are used to continuously monitor the ionosphere

HF Radar Example (CONUS-B)

The CONUS-B radar has the following parameters:

$P_t = 61$ dBW, $G_t = 23$ dB, $G_r = 28$ dB, $I_i = 3$ dB

two-way path gain factor, $(F_t)^2 = (F_r)^2 = 3$ dB, other system losses, 15 dB

noise power at the receiver, $k\mathrm{T}_s B_n = -164$ dBW

(a) What frequency should the radar use to detect a target with a wingspan of 15 m and what is the target's approximate RCS?

Assume horizontal polarization and model the wing as a shorted half-wave dipole to find the first resonant frequency (see the plot in the discussion of chaff):

$$l\,/\,2 = 15\text{ m} \Rightarrow f = 10\text{ MHz} \Rightarrow s\,/\,l^2 \approx 0.75 \Rightarrow s \approx 675\text{m}^2 = 28.5\text{ dB}$$

(b) If $SNR_{\min}$ = 25 dB, will the target be detected at 2000 km?

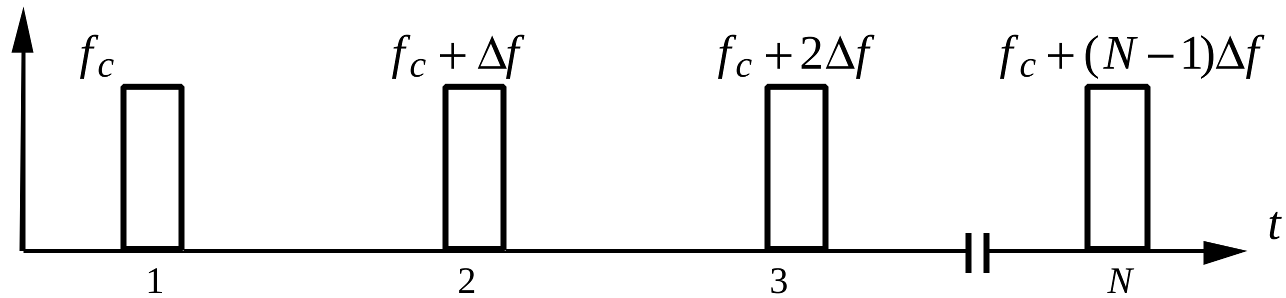
Compute the SNR. It is convenient to use dB quantities in this case:

$$SNR = \underbrace{P_t G_t G_r I_i}_{115} + \underbrace{(1/4p)^3}_{-33} - \underbrace{k\mathrm{T}_s B_n}_{-164} + \underbrace{\left(F_t F_r\right)^4}_{-6} + \underbrace{1/\left(R_t R_r\right)^2}_{-252} + \underbrace{s}_{28.5} + \underbrace{l^2}_{29.5} - \underbrace{L}_{15} = 31\text{ dB}$$

Since SNR > 25 dB the target will be detected. Note that the target RCS at resonance (see UWB lectures) can be 5-10 dB higher than at other frequencies, thus operating at resonance makes detection possible.

Stepped Frequency Radar (1)

In a stepped frequency radar the carrier frequency of each pulse in the train is increased



Receiver (instantaneous) bandwidth, $B_{\text{instant}} = 1/t$:

Controlled by the individual pulse
Determines the A/D sampling rate
$t\,\Delta f \le 1$

Effective bandwidth, $B_{\text{eff}} = N\Delta f$:

Controlled by the frequency excursion across the burst
Determines the range resolution

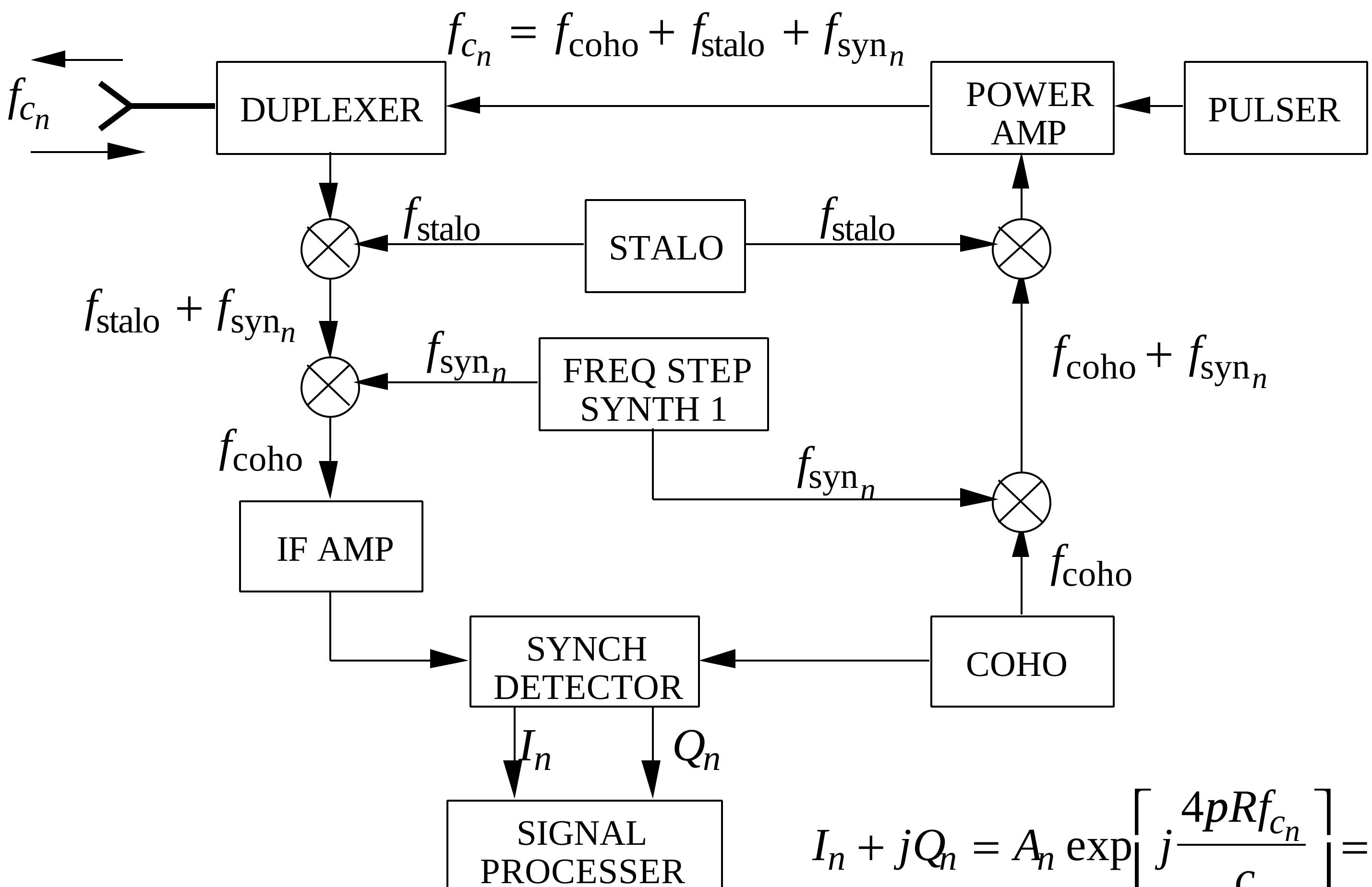
Stepped Frequency Radar (2)

Characteristics of stepped frequency radars:

1. Instantaneous bandwidth is controlled by the pulse width $B_{\text{instant}} = 1/t$
2. Range resolution is given by
$$\Delta R = \frac{c}{2N\Delta f} = \frac{c}{2B_{\text{eff}}}$$
that is determined by the effective bandwidth, $B_{\text{eff}} = N\Delta f$
3. The effective bandwidth can be increased semi-independently of the instantaneous bandwidth (the constraint is $t\,\Delta f \leq 1$)
4. It is possible to have a large effective bandwidth (and high range resolution) with low instantaneous bandwidth
5. Low instantaneous bandwidth allows a lower A/D sampling rate than a conventional radar (high frequency A/Ds are not commercially available). Narrowband microwave hardware is simpler and less expensive.

Stepped Frequency Radar (3)

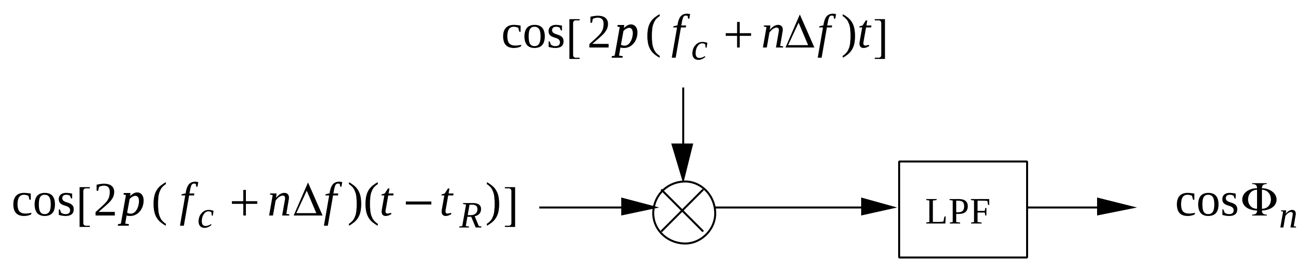
Block diagram:



$$I_n + jQ_n = A_n \exp\left[j\frac{4pRf_{c_n}}{c} \right] = A_n e^{j\Phi_n}$$

Stepped Frequency Radar (4)

Mathematical expression for phase shift:



$$\Phi_n = 2p(f_c + n\Delta f)t_R$$
$$= 2p(f_c + n\Delta f)\frac{2R_n}{c}$$

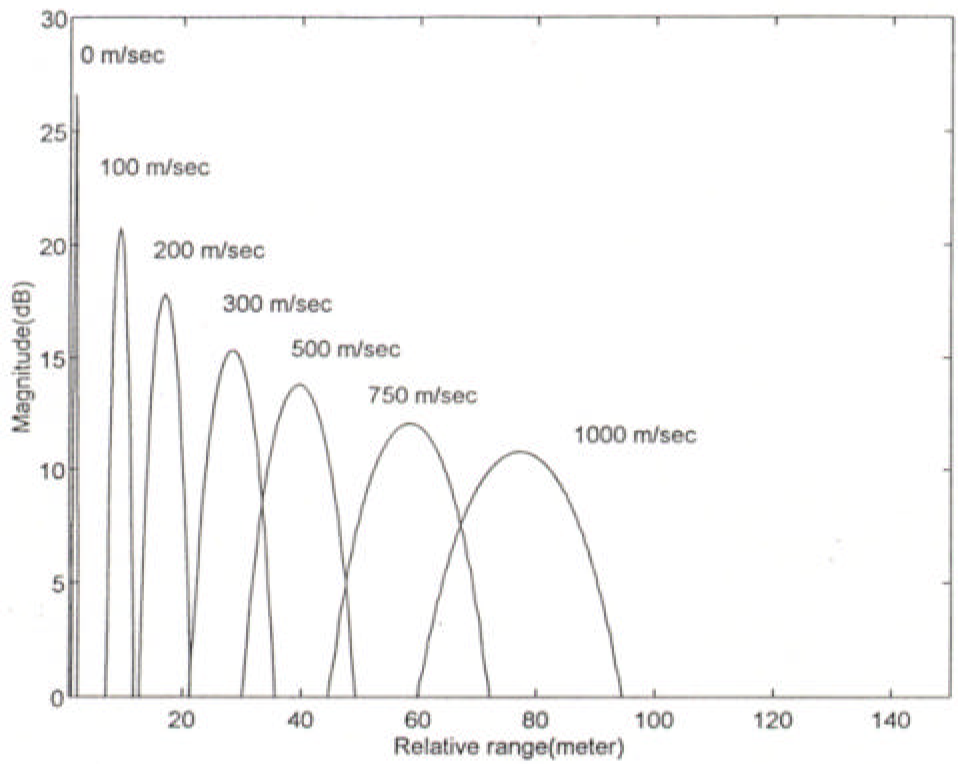
where $R_n = R_o + v_r n T_p$. Therefore,

$$\Phi_n = 2p(f_c + n\Delta f)\frac{2}{c}(R_o + v_r n T_p)$$
$$= \underbrace{\frac{4p\ f_c R_o}{c}}_{\substack{\text{PHASE SHIFT} \\ \text{DUE TO RANGE}}} + 2p \underbrace{\frac{\Delta f}{T_p}\frac{2R}{c}}_{\substack{\text{FREQ. SHIFT} \\ \text{DUE TO RANGE}}} T_p + 2p \underbrace{\frac{2v_r f_c}{c}}_{\substack{\text{DOPPLER} \\ \text{SHIFT}}} nT_p + 2p \underbrace{\frac{\Delta f}{T_p}\frac{2v_r n T_p}{c}}_{\substack{\text{DOPPLER} \\ \text{SPREAD}}} nT_p$$

Stepped Frequency Radar (5)

Doppler spreading, shifting and attenuation:

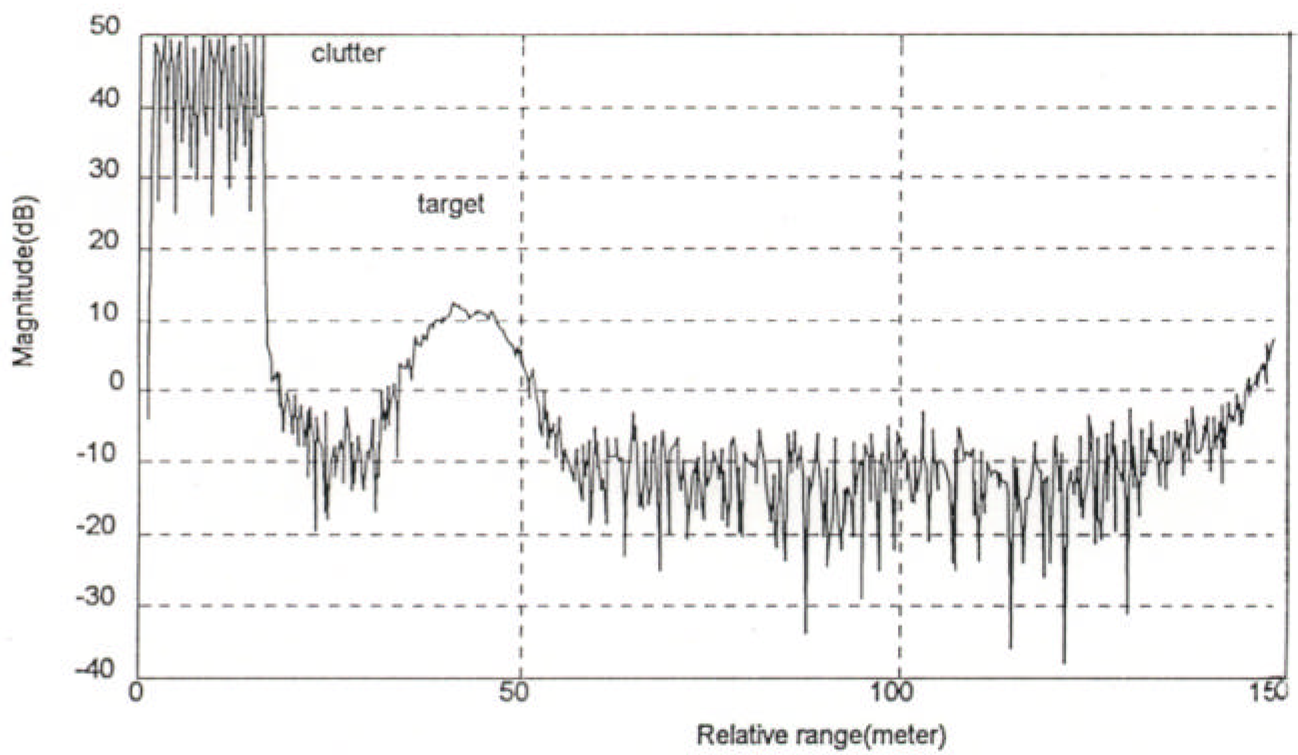
- Single target, different radial velocities
- Target range is unchanged
- SNR = 13 dB, PRF = 20 KHz, $f_c = 10$ GHz, $N = 512$, $\Delta f = 1$ MHz



Stepped Frequency Radar (6)

Doppler spreading and shifting can be used to separate targets from clutter:

- SNR = 11 dB, PRF = 20 KHz, CNR = 35 dB
- $f_c = 10$ GHz, $N = 512$, $\Delta f = 1$ MHz, $v_r = 500$ m/s
- If an estimate of the target velocity is available, velocity compensation can be applied



Imaging of Moving Targets

Objective is to find the reflectivity density function $r(x,y)$ from the frequency signature $S(f,t)$:

$$S(f,t) = e^{-j4pfR(t)/c} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} r(x,y) e^{-j4p\left[xf_x(t)+yf_y(t)\right]} dxdy$$

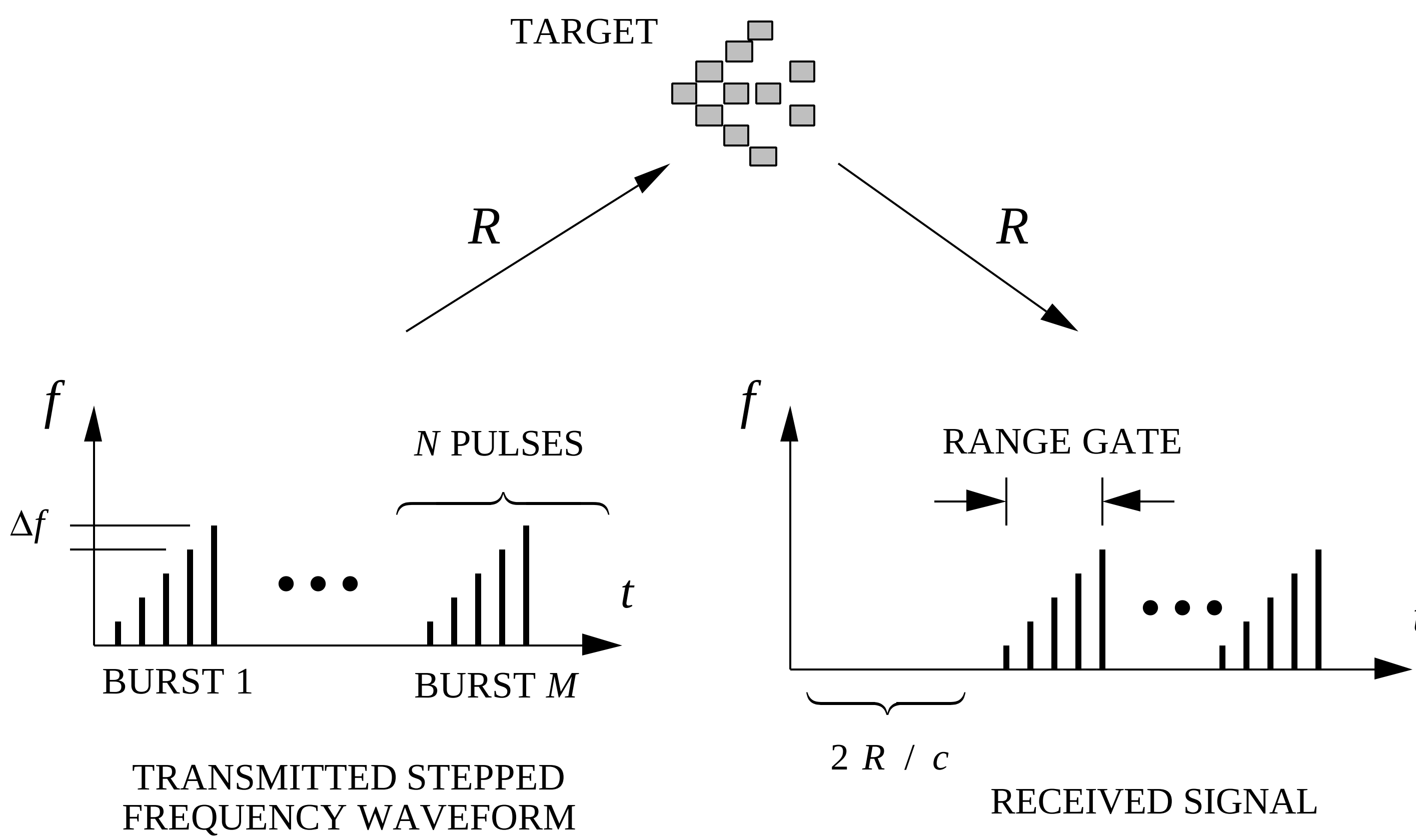
where the spatial frequencies are defined as

$$f_x(t) = \frac{2f}{c} \cos[f(t)] \quad \text{and} \quad f_y(t) = \frac{2f}{c} \sin[f(t)]$$

Stepped frequency imaging:

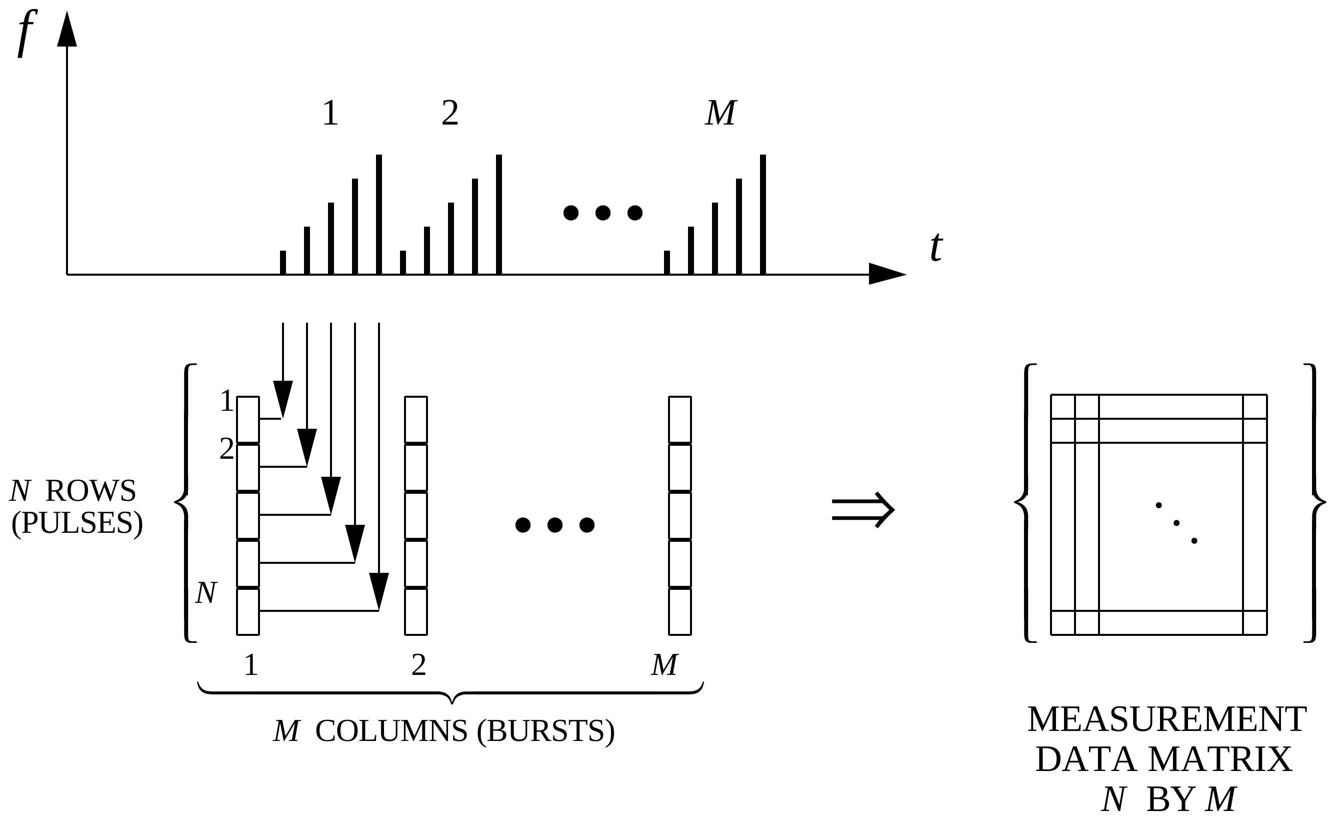
1. M bursts are transmitted, each containing N narrowband pulses
2. The center frequency f_n of each successive pulse is increased by a frequency step of Δf
3. Total bandwidth = $N\Delta f$
4. Cross range resolution determined by number of bursts, M

Stepped Frequency Imaging (1)



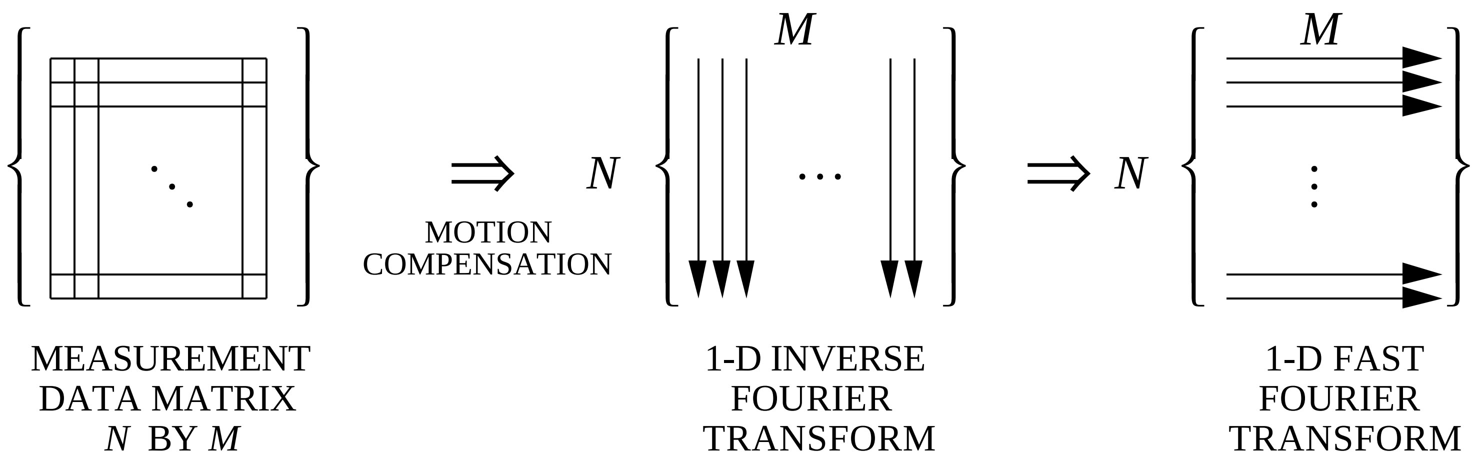
Stepped Frequency Imaging (2)

Form a two-dimensional matrix of measurement data $S(f_{nm}, t_{nm})$



Stepped Frequency Imaging (3)

Time-frequency transform for Doppler processing



1. Range processing: N-point 1-D inverse Fourier transform (1-DIFT) for each of the M received frequency signatures. M range profiles result, each with N range cells.
2. Cross range (Doppler) processing: for each range cell, the M range profiles are a time history that can be I and Q sampled and fast Fourier transformed. The result is an M- point Doppler spectrum or Doppler profile.
3. Combine the M range cell data and the M Doppler data to form a two-dimensional image.

Ultra-Wide Band Radar (1)

Ultra-wideband radar (UWB) refers to a class of radars with a large relative bandwidth. They include:

1. pulse compression radar
2. stepped frequency radar
3. impulse (monocycle) radar

Impulse radars have all the advantages of conventional short pulse radars. In addition, claims have also been made in the categories of (1) improved radar performance, and (2) ability to defeat stealth. We examine the validity of the claims (ref: Proceedings of the First Los Alamos Symposium on UWB Radar, Bruce Noel, editor):

Claim: Penetrates absorbers because of molecular resonances.
Validity: True, but the effect appears to be weak.

Claim: Defeats target shaping techniques.
Validity: True at low frequencies, but above certain frequencies shaping is wideband.

Claim: Excites target "aspect-independent" resonances.
Validity: True, but weak resonances; not exploitable at present.

Claim: Defeats RCS cancelation schemes.
Validity: True, but so do conventional wideband radars.

Ultra-Wide Band Radar (2)

Claim: Reduced clutter because it operates in the pulsewidth limited condition.
Validity: True, but negated by changes in clutter statistics, which vary rapidly with frequency.

Claim: Defeats multipath.
Validity: True, but multipath is often an advantage.

Claim: Overcomes the $1/R^2$ spreading loss by "extending" the near field.
Validity: True, but not exploitable at moderate to long ranges of interest for search radars.

Claim: Low probability of intercept (LPI).
Validity: True in general, but not necessarily for long range radars.

Claim: Resistance to jamming (short pulse implies narrow range gates and therefore not susceptible to CW jamming).
Validity: True

Claim: Target identification capability.
Validity: True, but need matched filters derived from all target signature features.

Ultra-Wide Band Radar (3)

Many of our assumptions used to model radar systems and components no longer are valid. For instance,

propagation characteristics,
target RCS,
antenna gain, and
radar device characteristics,

are not independent of frequency because the bandwidth is so large. The frequency dependence of the system parameters must be included:

$$P_r = \frac{P_t(f)G_t(f)\sigma(f)A_{er}(f)}{(4\pi R^2)^2}$$

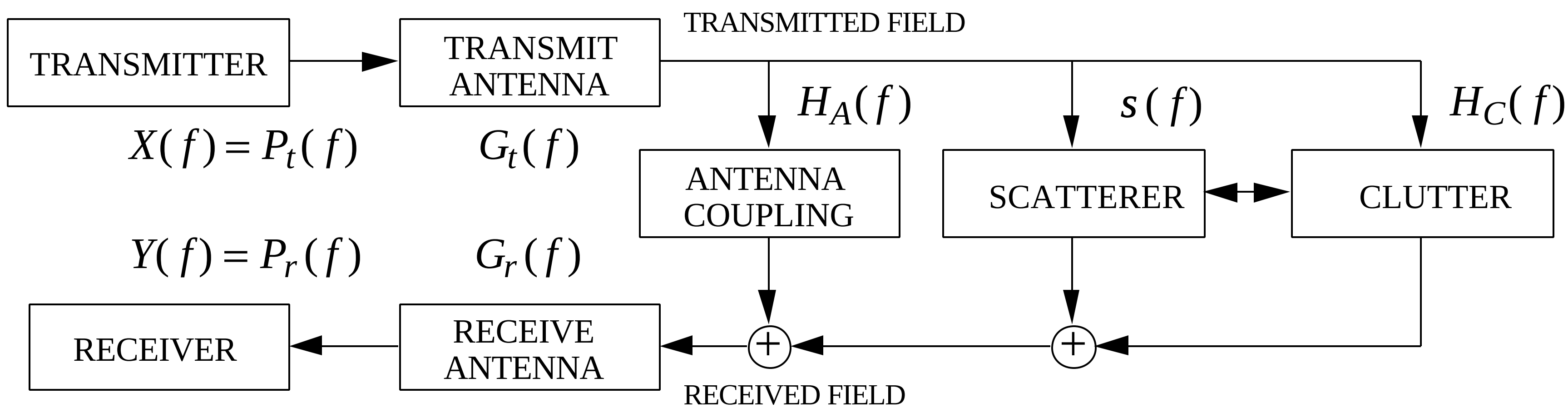
Important points:

1. The waveform out of the transmitter is not necessarily the waveform that is radiated by the antenna. The antenna removes the DC and some low frequency components. The radiated signal is the time derivative of the input signal.
2. The waveform reflected by the target is not necessarily the waveform incident on the target.
3. The waveform at the receive antenna terminals is not necessarily the waveform at the antenna aperture.

To extract target information requires a substantial amount of processing.

Ultra-Wide Band Radar (4)

Wideband model of the radar, target, and environment:



excitation waveform:	$x(t) \leftrightarrow X(f)$	transmit antenna:	$g_t(t) \leftrightarrow G_t(f)$
clutter environment:	$h_C(t) \leftrightarrow H_C(f)$	receive antenna:	$g_r(t) \leftrightarrow G_r(f)$
antenna coupling:	$h_A(t) \leftrightarrow H_A(f)$	target:	$s(t) \leftrightarrow s(f)$
noise:	$n(t) \leftrightarrow N(f)$	received signal:	$y(t) \leftrightarrow Y(f)$

The target's scattered field can be determined from $Y(f)$ if all of the other transfer functions are known. If they are not known they must be assumed.

Ultra-Wide Band Radar (5)

In general: 1. Antenna radiation requires acceleration of charge.
2. The radiated signal is the time derivative of the input signal.

From the definition of magnetic vector potential, $\vec{B} = \mu\vec{H} = \nabla \times \vec{A}$. Take the derivative with respect to time

$$\mu \frac{\partial}{\partial t}\vec{H} = \frac{\partial}{\partial t}(\nabla \times \vec{A}) = \nabla \times \left(\frac{\partial}{\partial t}\vec{A}\right)$$

Substitute this into Maxwell's first equation:

$$\nabla \times \vec{E} = -\mu \frac{\partial}{\partial t}\vec{H} = -\nabla \times \left(\frac{\partial}{\partial t}\vec{A}\right)$$

implies

$$\vec{E} = \frac{\partial}{\partial t}\vec{A}$$

But the magnetic vector potential is proportional to current. As an example, for a line current

$$\vec{A}(t,R) = \frac{\mu}{4\pi}\int_L \frac{I(t - R/c)}{R}\, d\ell$$

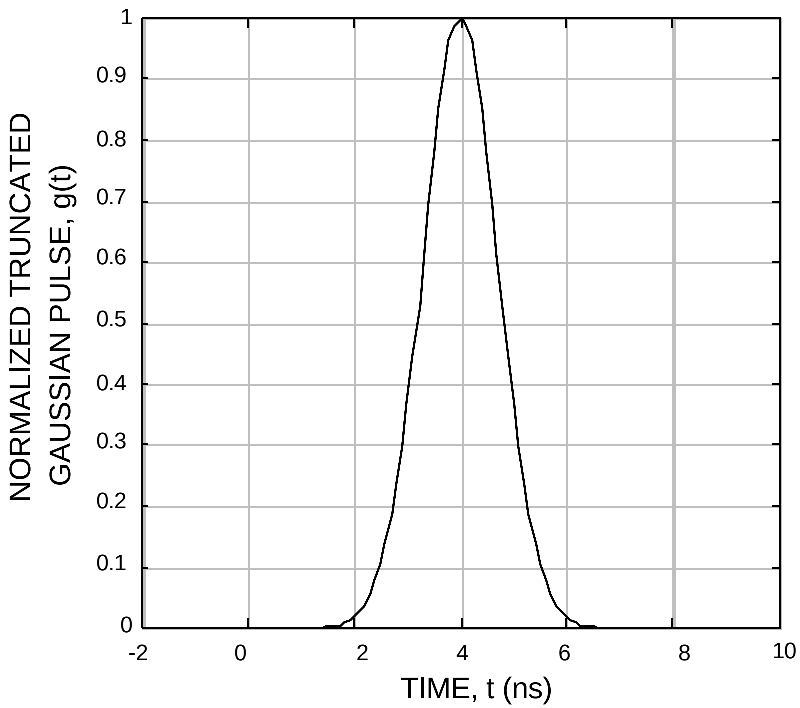
Therefore $\vec{E} \propto \dfrac{\partial I}{\partial t}$ and the radiated field strength depends on the acceleration of charge.

Ultra-Wide Band Radar (6)

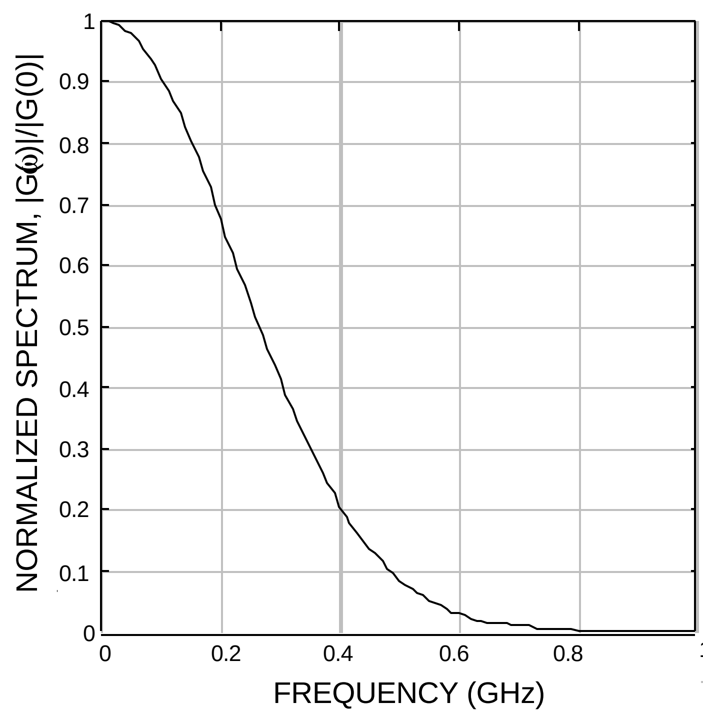
UWB waveforms: <u>gaussian pulse</u>

1. has the minimum time-bandwidth product of all waveforms
2. spectrum has a dc component; therefore it cannot be radiated
3. used analytically because it is mathematically convenient

Truncated gaussian pulse



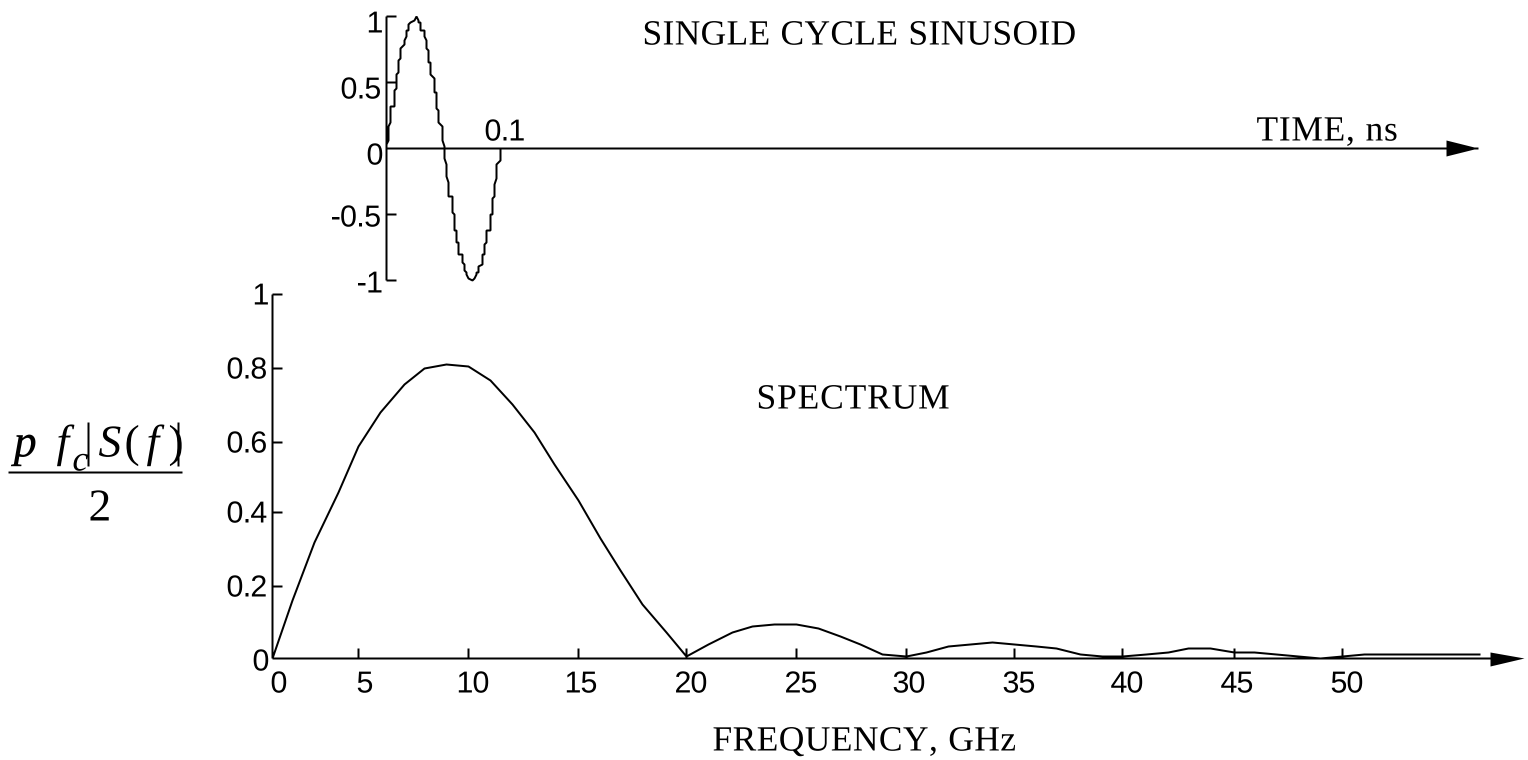
Frequency spectrum



Ultra-Wide Band Radar (7)

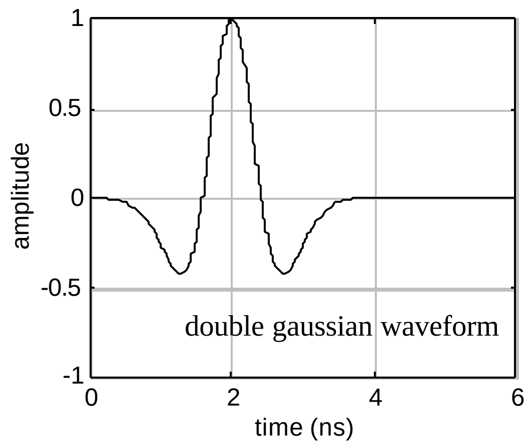
UWB waveforms: <u>single cycle sinusoid</u>

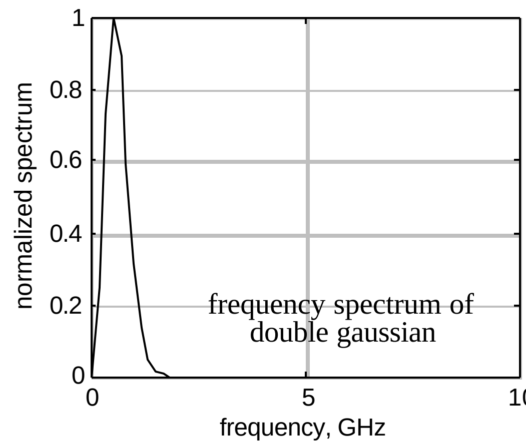
1. its frequency spectrum has no dc component and therefore it can be radiated
2. relatively convenient mathematically
3. hard to achieve with hardware



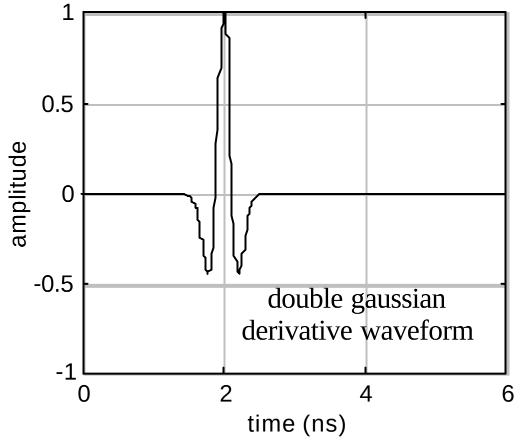
Ultra-Wide Band Radar (8)

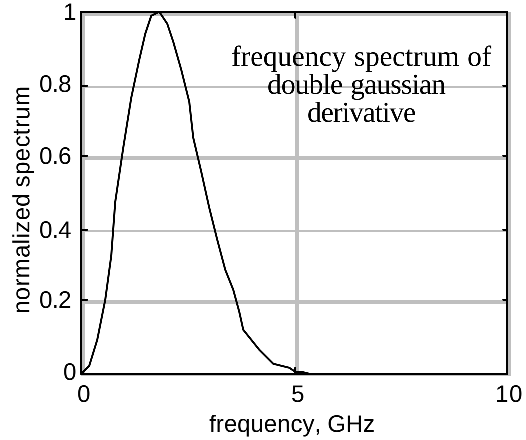
Double gaussian: $s(t) = A_1 e^{-a_1 (t-t_o)^2} - A_2 e^{-a_2 (t-t_o)^2}$





Double gaussian derivative: $s(t) = \left(1 - \frac{4p}{t_m}(t-t_o)^2\right)\exp\left(-\frac{2p}{t_m}(t-t_o)^2\right)$





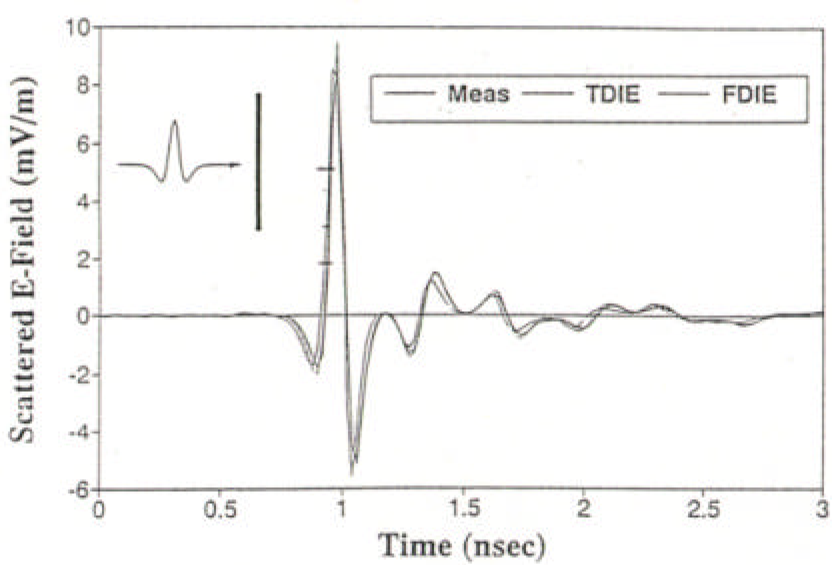
RCS Considerations

- Target illumination and matched filtering:
    - For very short pulses the entire target may not be illuminated simultaneously. Therefore the time response (shape) depends on angle.
    - The time response differs with each target. The basis of matched filter design no longer holds.
- Target resonances:
    - Resonances are a characteristic of conducting structures
    - Standing waves are set up on the structure when its dimension is approximately an integer multiple of a half wavelength
    - The standing waves result in enhanced RCS relative to that at non-resonant frequencies
    - In general, a target has many resonant frequencies due to its component parts (for example, aircraft: wings, fuselage, vertical tail, etc.)
    - Applications:
        1. Detection: given a specific target to be detected, use a knowledge of its resonant frequencies to take advantage of the enhanced RCS
        2. Identification (ID): when a target is detected, examine its resonant frequencies to classify it
    - Nonconducting (lossy) structures also have resonances, but the RCS enhancement is not as strong as it is for a similar conducting structure

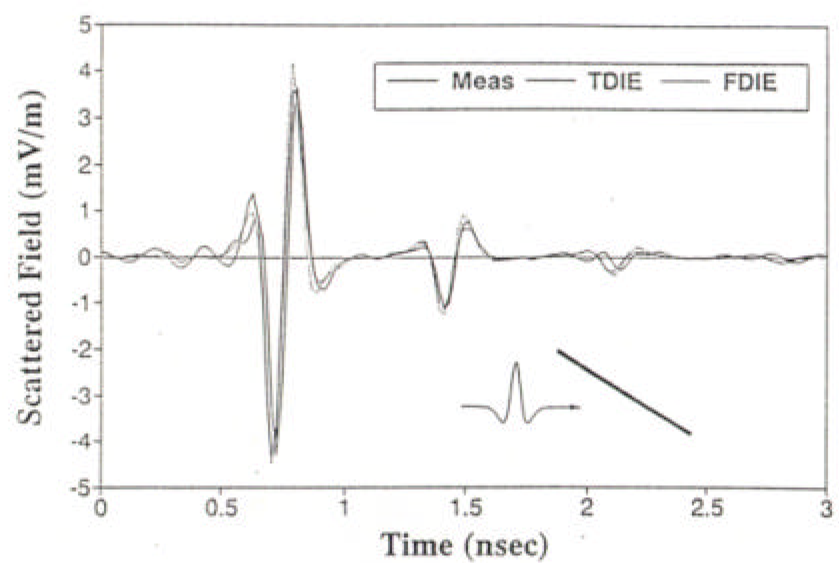
Time Domain Scattering

- Double gaussian incident wave
- Thin wire target

Normal incidence

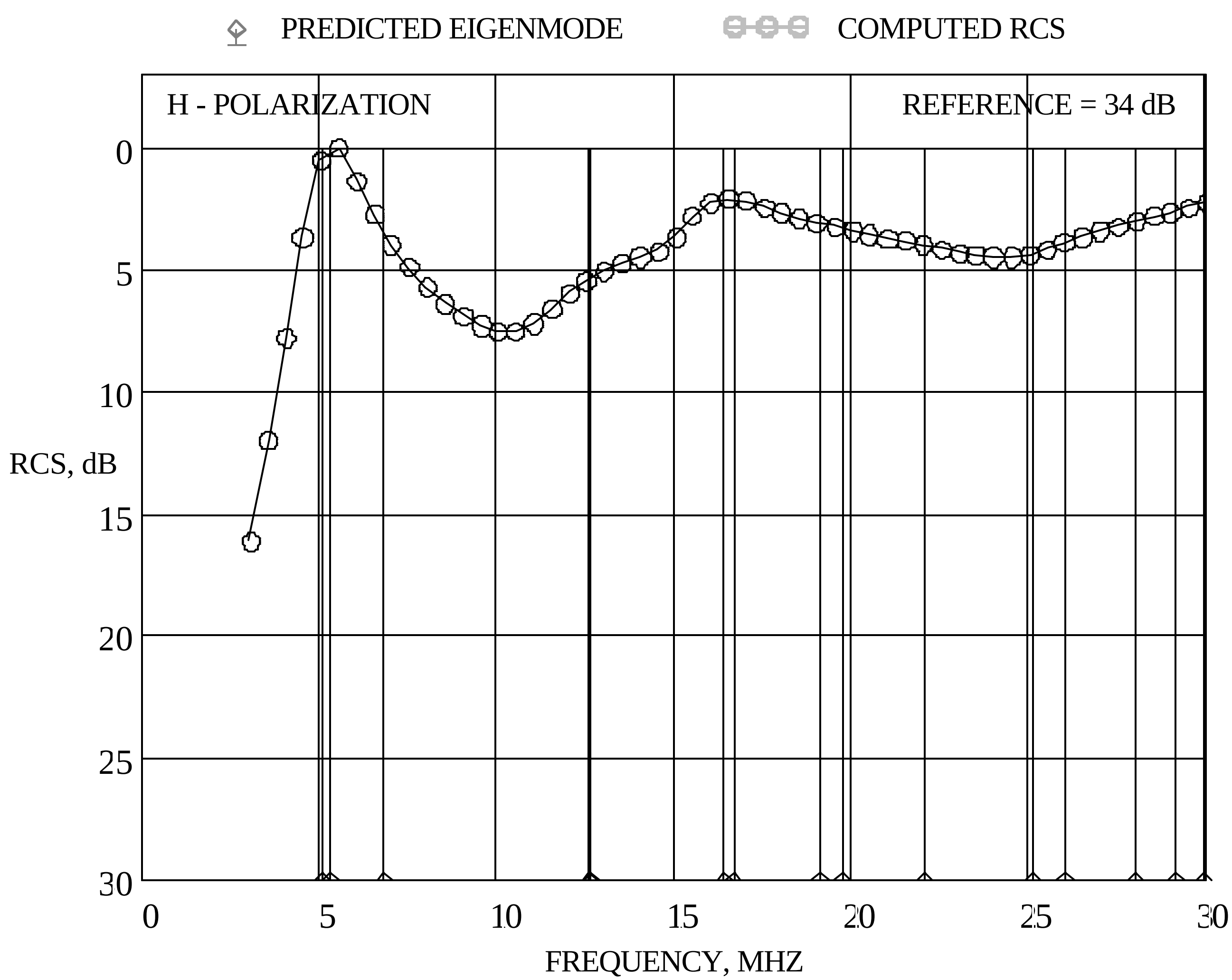


Oblique incidence (60 degrees)



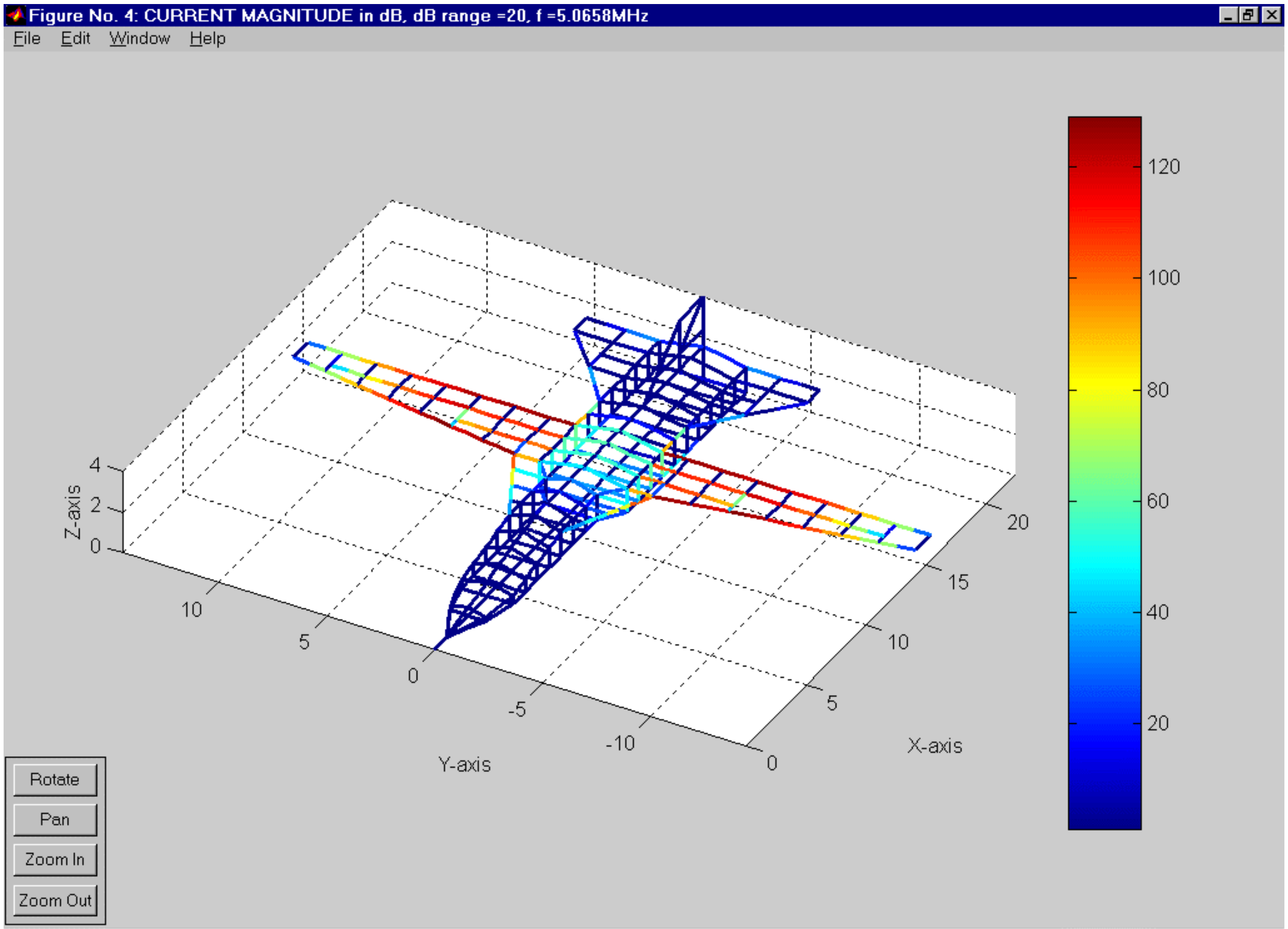
(From Morgan and Walsh, IEEE AP-39, no. 8)

F-111 Resonant Frequencies



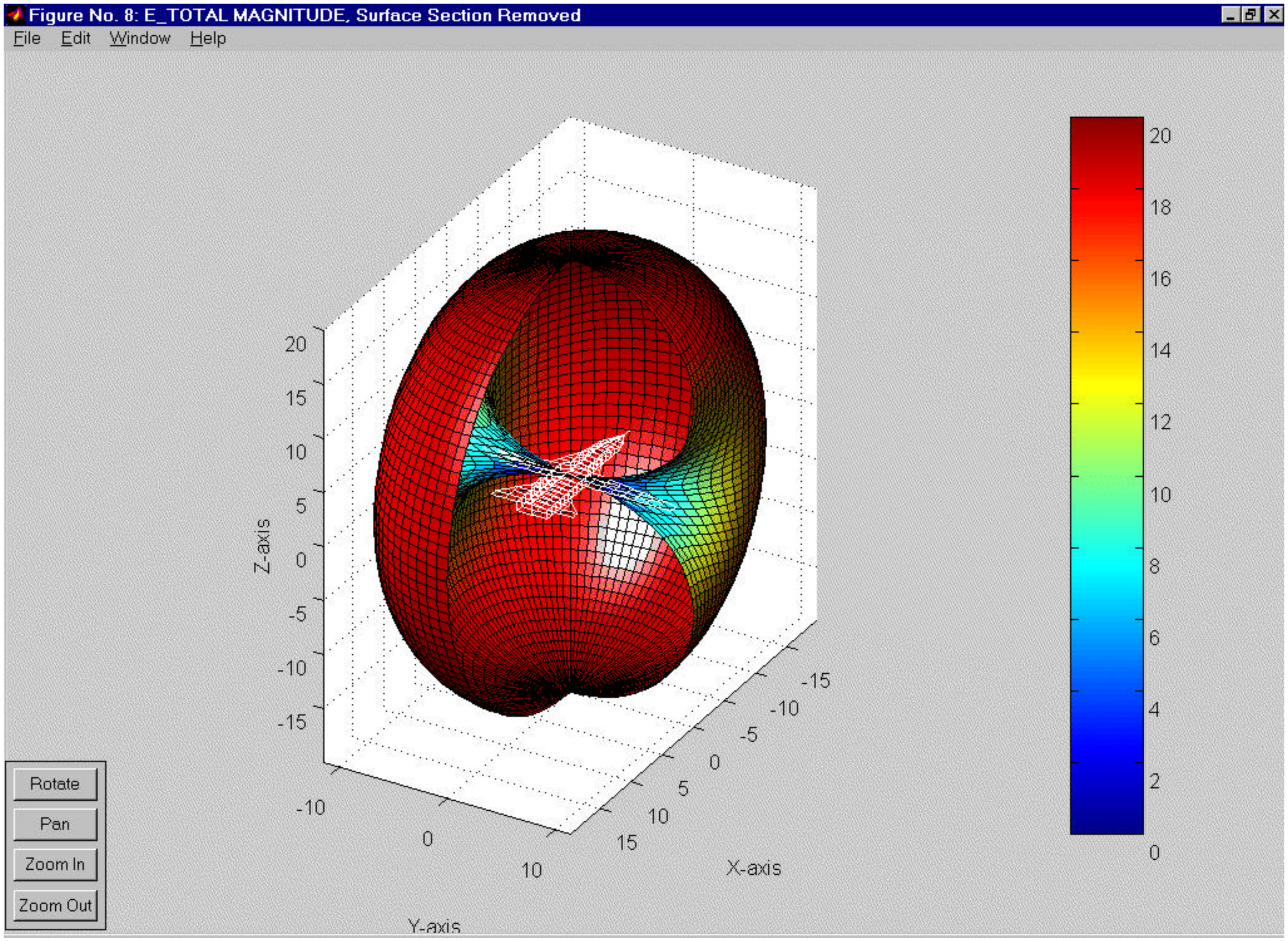
(From Prof. Jovan Lebaric, *Naval Postgraduate School*)

Currents on a F-111 at its First Resonance



(From Prof. Jovan Lebaric, *Naval Postgraduate School*)

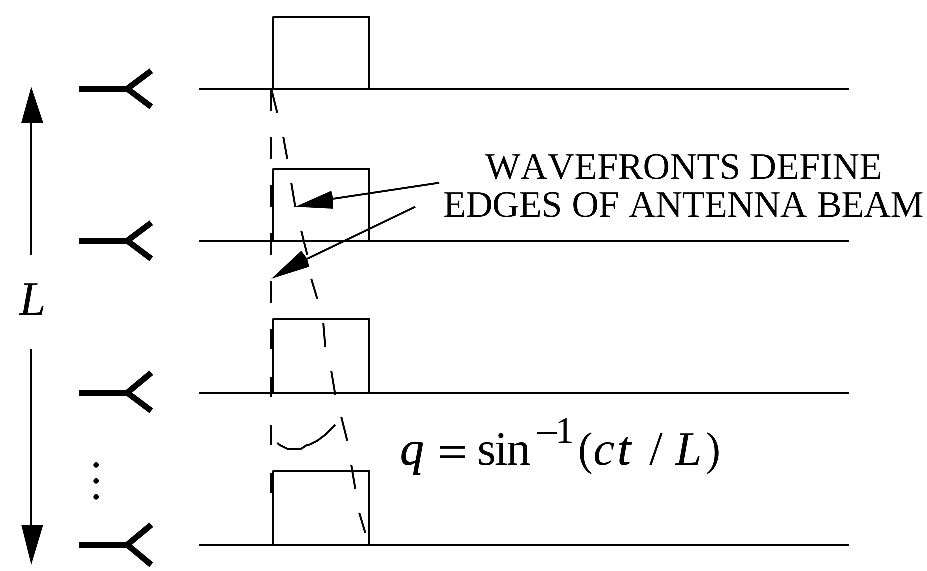
Excitation of the First Resonance



(From Prof. Jovan Lebaric, *Naval Postgraduate School*)

Antenna Considerations

1. Referring to the UWB form of the RRE, the antenna gain aperture product $G_t A_{er}$ should be independent of frequency. This cannot be achieved with a single antenna.
2. Low gain antennas have been used successfully. High gain antennas are not well understood.
3. Beamwidth depends on the time waveform. Example: pulse radiated from an array.

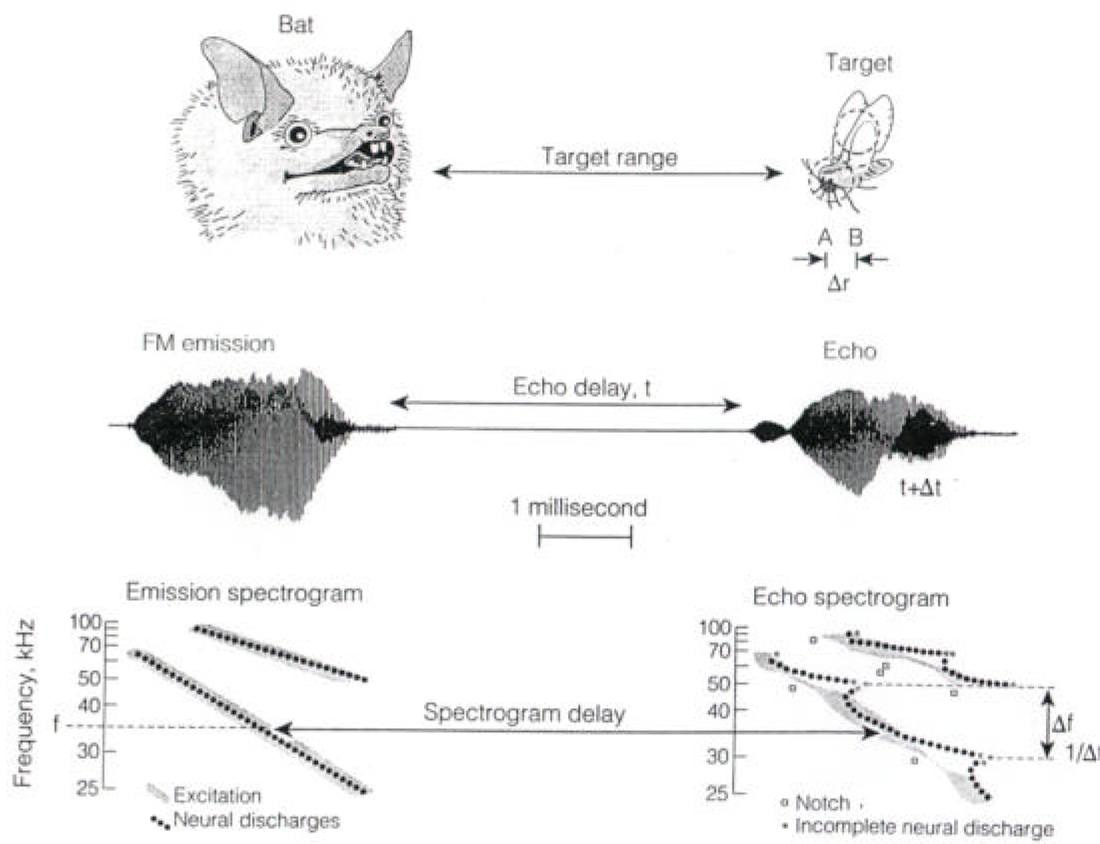


Brown Bat Ultrasonic Radar (1)

Bats navigate and capture insects by an echo location technique that combines time and frequency domain operations. It has lead to the imaging technique called spectrogram correlation and transformation (SCAT).

- Frequency range:
  15-150 kHz
- Sweeps two frequency ranges simultaneously:
  50-22 kHz
  100-44 kHz
- Linear FM waveform (chirp)
- Integration time:
  350 ms

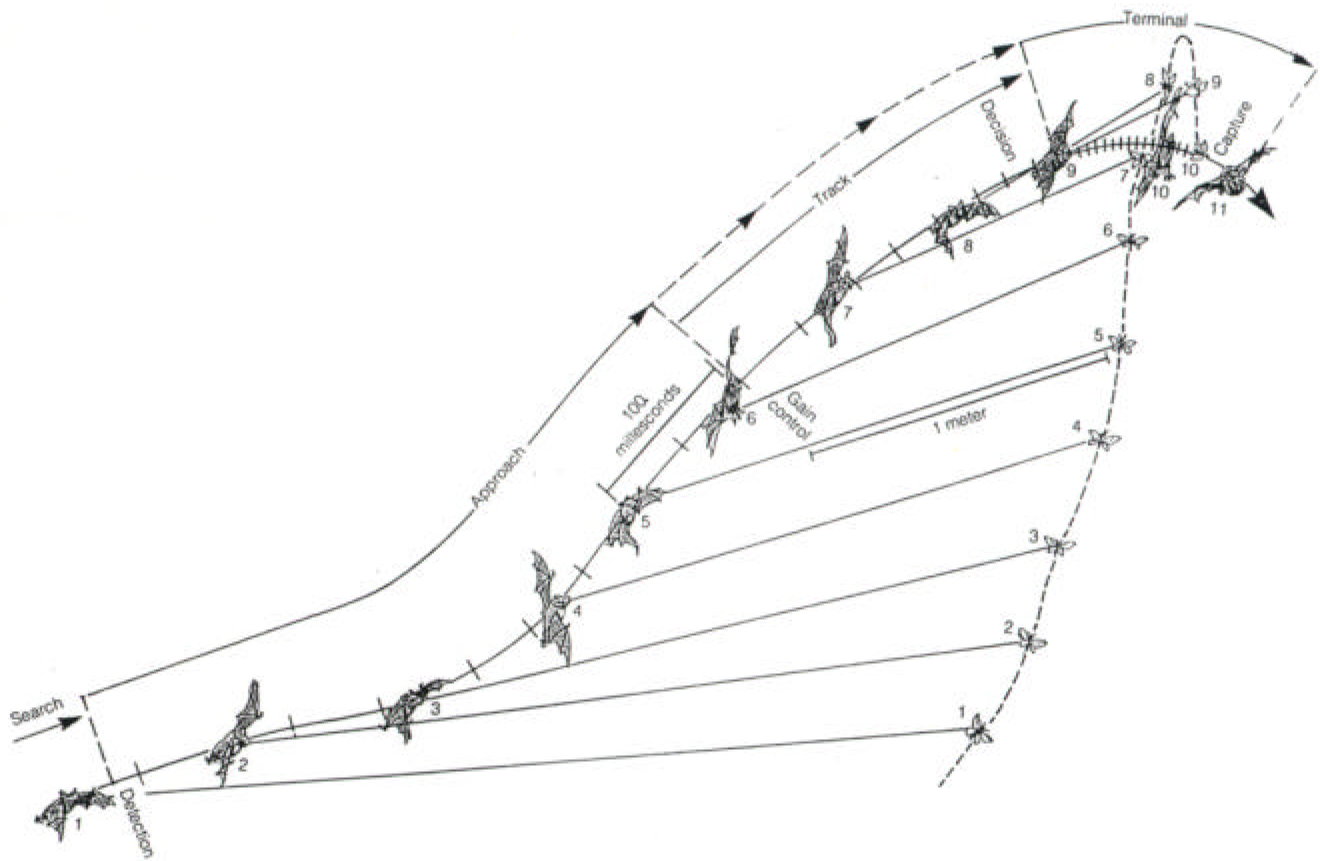
(From IEEE Spectrum, March 1992, p. 46)



Brown Bat Ultrasonic Radar (2)

Bat pursuing prey:

- Typical target (insect) flutter rate: 10-100 Hz
- Hash marks denote positions of chirp emission



(From: *IEEE Spectrum*, March 1992, p. 46)

Doppler Weather Radar (1)

The echo from weather targets (rain, snow, ice, clouds, and winds) can provide information that can be used to map precipitation and wind velocity.

Reflectivity measurements are used to estimate precipitation rates (echo power is the zeroth moment of the Doppler spectrum). Higher moments of the Doppler spectrum yield additional information:

1. Mean doppler velocity (first moment normalized to the zeroth moment)

$$\bar{v} = \frac{\int_{-\infty}^{\infty} v\, S(v)\, dv}{\int_{-\infty}^{\infty} S(v)\, dv}$$

gives a good approximation to the radial component of the wind.

2. Spectrum width, s_v (square root of the second moment about the first moment of the normalized spectrum)

$$s_v^2 = \frac{\int_{-\infty}^{\infty} (v-\bar{v})^2\, S(v)\, dv}{\int_{-\infty}^{\infty} S(v)\, dv}$$

is a measure of the deviation of the velocities of particles from the average. It is an indication of turbulence and shear.

The doppler spectrum's zero and second moments can be estimated by noncoherent radars, but only coherent radars can measure the first moment.

Doppler Weather Radar (2)

Radar primarily measures scattering from rain, snow and ice particles. Typical frequencies are in the L, S and C bands (1 to 8 GHz). The scattering particles are in the Rayleigh region. The RCS of an individual particle is given by

$$s_i = \frac{p^5}{l^4}\left|\frac{m^2-1}{m^2+2}\right|^2 D_i^6 = \frac{p^5}{l^4}|K|^2 D_i^6$$

where $m = n - jn' = \sqrt{e_c}$ is the complex index of refraction ($e_c = e' - je''$ is the complex dielectric constant) and D the diameter of the particle. Values of $|K|^2$ are in the range of 0.91 to 0.93 for $0.01 \le l \le 0.1$. Define the <u>target reflectivity</u> Z of N particles in volume ΔV:

$$s = \sum_{i=1}^{N} s_i \equiv h(\Delta V) = \left(\frac{p^5}{l^4}|K|^2 Z\right)(\Delta V) \quad \text{where} \quad Z = \frac{1}{\Delta V}\sum_{i=1}^{N} D_i^6$$

Assume: 1. precipitation particles are homogeneous dielectric spheres
2. all particles in ΔV have the same $|K|^2$ and D
3. the radar resolution volume ΔV it is completely filled with particles
4. multiple scattering is neglected

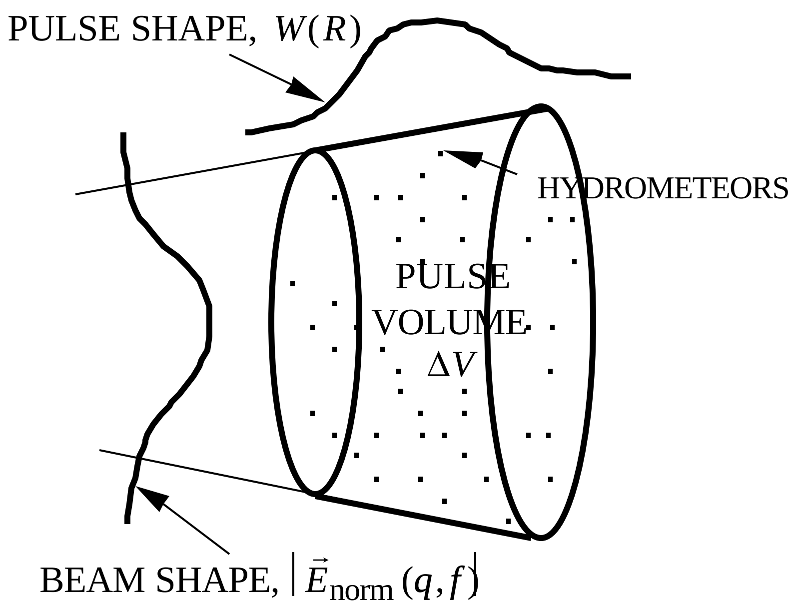
Note: Some Skolnik formulas assume a volume of 1 m^3, and therefore ΔV (or his V_c) does not appear explicitly in his equations.

Doppler Weather Radar (3)

Weather radar equation for the average power received from a single particle

$$\overline{P}_r = \frac{P_t G^2 \lambda^2 \sigma_i}{(4\pi)^3 L_i^2 R_i^4}$$

The one-way atmospheric attenuation loss is $1/L_i = \exp\left[-2\int_0^{R_i} (\alpha_{\text{gas}} + \alpha_{\text{particles}})\, dR\right]$



The illumination of particles within a pulse volume (resolution volume) is not uniform:

1. there are azimuth and elevation tapers due to the beam shape $|\vec{E}_{\text{norm}}|$
2. there is a range taper due to the pulse shape and receiver frequency characteristic, $W(R_i)$

Assume that the weight functions are a maximum at the center of the cell, range R_o

Doppler Weather Radar (4)

Weather radar equation becomes

$$\overline{P}_r = \frac{P_t G_o^2 \lambda^2}{(4\pi)^3} \left(\sum_{i=1}^{N} \frac{\sigma_i \left|\vec{E}_{\text{norm}}\right|^4 W^2(R_i)}{L_i^2 R_i^4} \right)$$

Replace the summation with an integral and assume that the contributions to the integral from outside of the resolution cell are negligible

$$\overline{P}_r = \frac{P_t G_o^2 \lambda^2 \eta}{(4\pi)^3 L_a^2 R_o^4} \underbrace{\int_0^{\infty} W^2(R)\, R_o^2 \, dR \int_0^{\pi} \int_0^{2\pi} \left|\vec{E}_{\text{norm}}\right|^4 \sin\theta \, d\theta \, d\phi}_{\Delta V}$$

where L_a is the average atmospheric loss factor at range R_o. Assume a square gaussian shaped beam of the form $G(\theta,\phi) = G_o \left|\vec{E}_{\text{norm}}(\theta,\phi)\right|^2$ where

$$\left|\vec{E}_{\text{norm}}(\theta,\phi)\right|^2 = \exp\left\{-4\ln(2)\left(\theta^2/\theta_B^2 + \phi^2/\theta_B^2\right)\right\}$$

and the HPBW in both principal planes is θ_B. The antenna beam integral becomes

$$\int_0^{\pi}\int_0^{2\pi} \left|\vec{E}_{\text{norm}}\right|^4 \sin\theta \, d\theta \, d\phi = \frac{\pi \theta_B^2}{8\ln(2)}$$

Doppler Weather Radar (5)

The range illumination not only depends on the pulse shape, but also the receiver frequency characteristic. In general

$$\int_0^\infty W^2(R_i)\,dR = \frac{1}{L_r}\frac{ct}{2}$$

where $1/L_r$ is the receiver loss factor due to finite bandwidth. For a rectangular pulse and a gaussian frequency characteristic with $B_6 t \approx 1$ the loss is 2.3 dB. (In meteorological applications it is customary to use the 6 dB bandwidth of the receiver, B_6.) The radar equation becomes:

$$\overline{P}_r = \frac{P_t G_o^2\, l^2 h p\, q_B^2}{(4p)^3 R_o^2 L_a^2 L_r 8 \ln 2}\,\frac{ct}{2}$$

The signal-to-noise ratio is proportional to $\dfrac{ct^{\,2}}{L_r B_6 t}$. Unlike point targets, the maximum SNR does not necessarily occur for $B_6 t \approx 1$. The optimum SNR consists of a matched gaussian filter and pulse that together yield the desired resolution.

Note: Skolnik has an additional $p/4$ in the clutter volume for an elliptical beam cross section, as opposed to the square beam cross section that we used.

Implementation and Interpretation of Data (1)

1. Spectral broadening is approximately gaussian with a variance

$$s_v^2 = s_s^2 + s_m^2 + s_d^2 + s_t^2$$

where the sources are: shear, s_s^2
antenna modulation, s_m^2
different particle fall rates, s_d^2
turbulence, s_t^2

Large spectral widths (≥ 5 m/s) are associated with turbulent gusts (≥ 6 m/s).

2. Requirement for echo coherency: want large T_p for large R_u but small T_p is desired so that the returns from pulse to pulse are correlated. Typical guideline

$$\frac{l}{2T_p} \geq 2ps_v \quad \Rightarrow \quad \frac{c\,l}{4R_u} \geq 2ps_v$$

3. A single doppler radar can map the field of radial velocity. Two nearly orthogonal radars can reconstruct the two-dimensional wind field in the planes containing the radials.

Implementation and Interpretation of Data (2)

4. When the assumptions about the scattering particles are not valid then an effective radar reflectivity can be used. (It is the equivalent Z for spherical water drops that would give the same echo power as the measured reflectivity.)

$$Z_e = \frac{Z l^4}{p^5 |K_w|^2}$$

where K_w denotes water. The units of dBZ are sometimes used

$$\mathrm{dBZ} = 10 \log_{10}\left(\frac{Z,\ \mathrm{mm}^6/\mathrm{m}^3}{1\ \mathrm{mm}^6/\mathrm{m}^3} \right)$$

Typical values:

Z_e dBZ	Precipitation Rate (mm/hr) 1	10
rain	23	39
snow	26	48

Implementation and Interpretation of Data (3)

5. The echo sample voltage from N_s scatterers at time t_n is of the form

$$V(t_n) \propto \sum_{i=1}^{N_s} A_i(R_i(t_n)) \exp\{j2kR_i(t_n)\}$$

where A_i depends on s_i, $\left|\vec{E}_{\text{norm}}(q_i, f_i)\right|^4$ and $B_6 t$. The power averaged over one cycle is

$$\overline{P}(t_n) \propto \frac{1}{2}\{VV^*\} = \frac{1}{2} \sum_{p=1}^{N_s} \sum_{q=1}^{N_s} A_p A_q^* \exp\{j2k(R_p - R_q\}$$

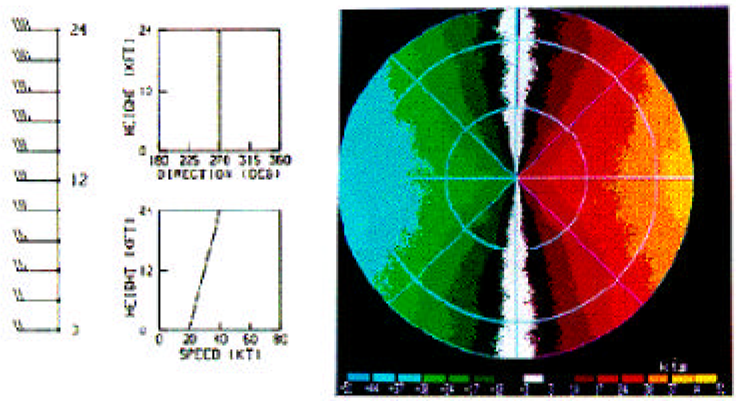
$$\overline{P}(t_n) \propto \underbrace{\frac{1}{2} \sum_{p=1}^{N_s} \left|A_p\right|^2}_{\text{INCOHERENT SCATTER}} + \underbrace{\frac{1}{2} \sum_{\substack{p=1 \\ p \neq q}}^{N_s} \sum_{q=1}^{N_s} A_p A_q^* \exp\{j2k(R_p - R_q\}}_{\text{COHERENT SCATTER}}$$

The second term is negligible for spatially incoherent scatter, but is significant for scattering from particles that have their positions correlated. An example is Bragg scatter from spatially correlated refractivity fluctuations. Bragg scatter is usually negligible for precipitation backscatter, but not clear air echoes (Angel echoes).

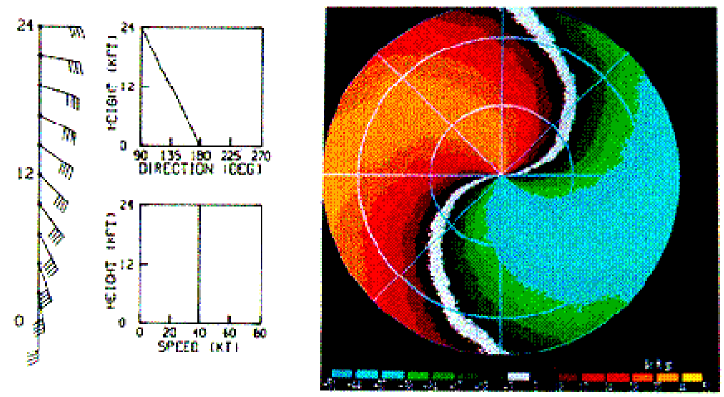
Implementation and Interpretation of Data (4)

Sample PPI displays for wind velocity variations (from Brown & Wood)

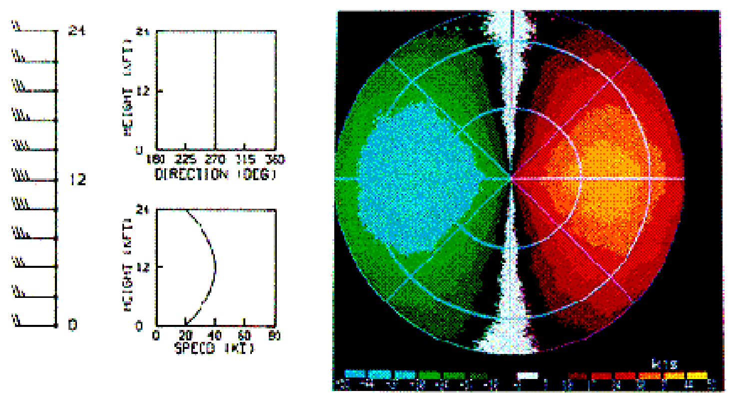
Uniform direction, linear variation with height



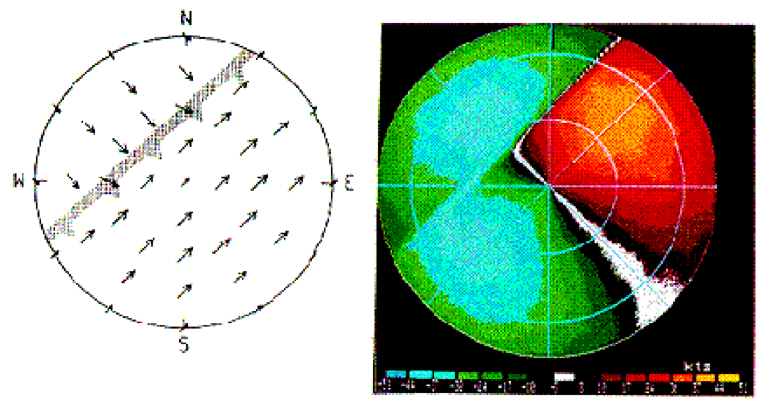
Uniform speed, linear direction change with height



Uniform direction, nonlinear variation with height



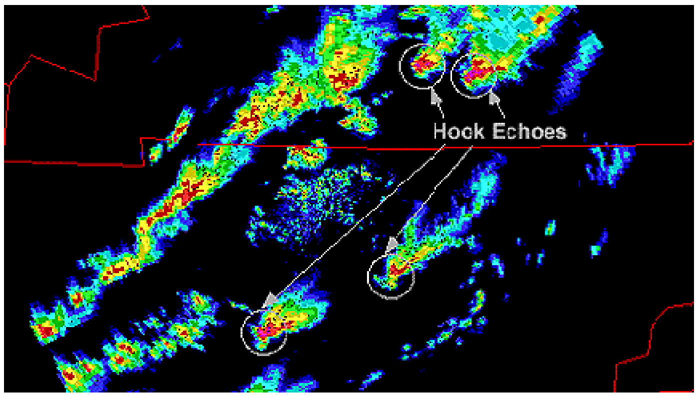
Wind shear

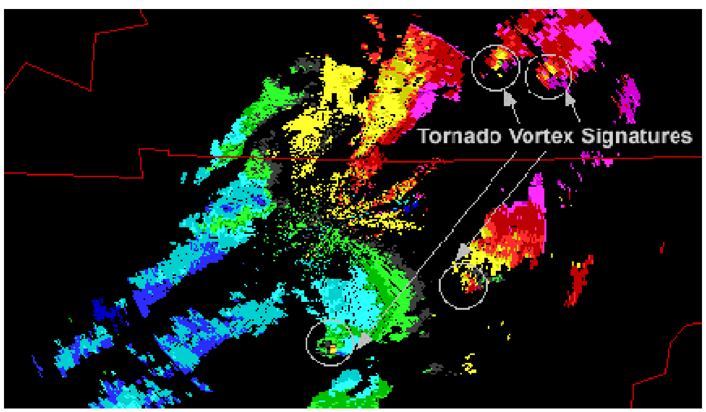


Implementation and Interpretation of Data (5)

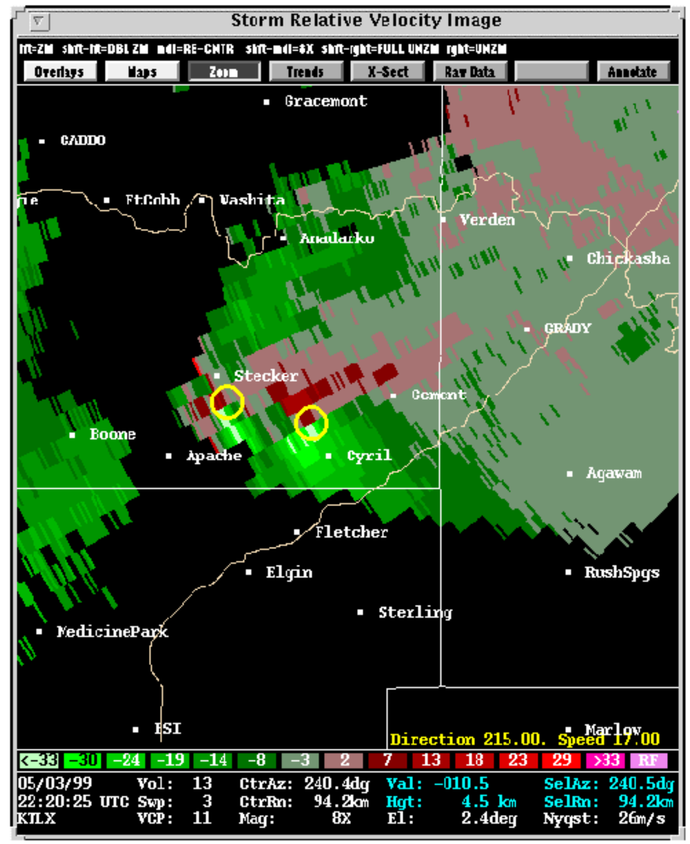
Weather images (from Brown & Wood)

Tornadoes are often located at the end of hook-shaped echoes on the Southwest side of storms



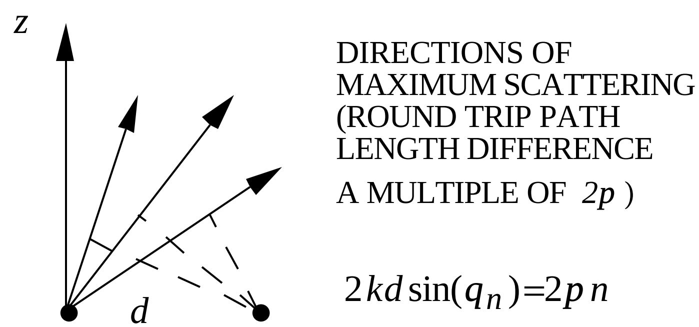


Tornado vortex signature (TVS): central pixels near the beam axis indicate exceptionally strong winds



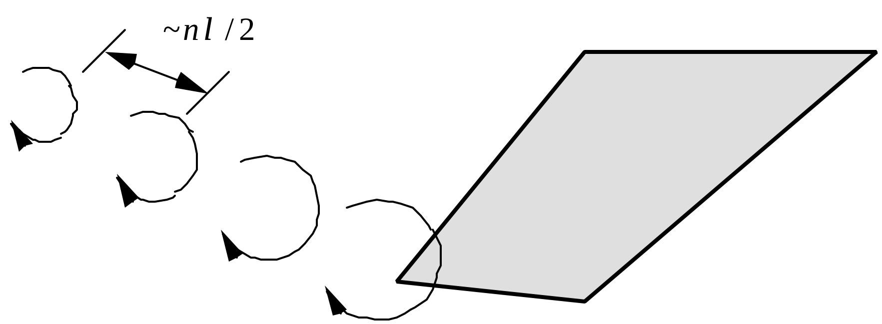
Clear Air Echoes and Bragg Scattering

Bragg scatter occurs when the round trip path length difference between periodic scattering elements is an integer multiple of $2p$



$$2kd\sin(q_n)=2p\,n$$

Periodic variations in the index of refraction occur naturally (locally periodic turbulence and waves, insect swarms, birds, etc.) Echoes from these sources are called Angel returns. Another example is wing tip vortices from an aircraft.



Weather Radar Example

Radar with beamwidth of 0.02 radians tracks a 0.1 square meter target at 50 km. Find the signal to clutter ratio if $\eta = 1.6\times10^{-8}\ \mathrm{m}^2/\mathrm{m}^3$ and $\tau = 0.2\ \mu\mathrm{s}$

Clutter return: $$C = \bar{P}_r = \frac{P_t G_o^2 \lambda^2 \eta \pi \theta_B^2}{(4\pi)^3 R^2 L_a^2 L_r 8\ln 2}\,\frac{c\tau}{2}$$

Target return: $$P_r = \frac{P_t G_o^2 \lambda^2 \sigma}{(4\pi)^3 R^4 L_a^2 L_r}$$

Assume all losses are the same for the target and clutter. Therefore, the power ratio becomes

$$SCR = \frac{P_r}{\bar{P}_r} = \frac{\sigma_t\, 16\ln 2}{\theta_B^2 \pi c \tau \eta R_o^2}$$

$$SCR = \frac{(0.1)(16)\ln 2}{\pi\left(0.02^2\right)\left(3\times10^8\right)\left(0.2\times10^{-6}\right)\left(1.6\times10^{-8}\right)50000^2}$$

$$SCR = 0.368 = -4.3\ \mathrm{dB}$$

Monolithic Microwave Integrated Circuits

- Monolithic Microwave Integrated Circuits (MMIC): All active and passive circuit elements, components, and interconnections are formed into the bulk or onto the surface, of a semi-insulating substrate by some deposition method (epitaxy, ion implantation, sputtering, evaporation, or diffusion)

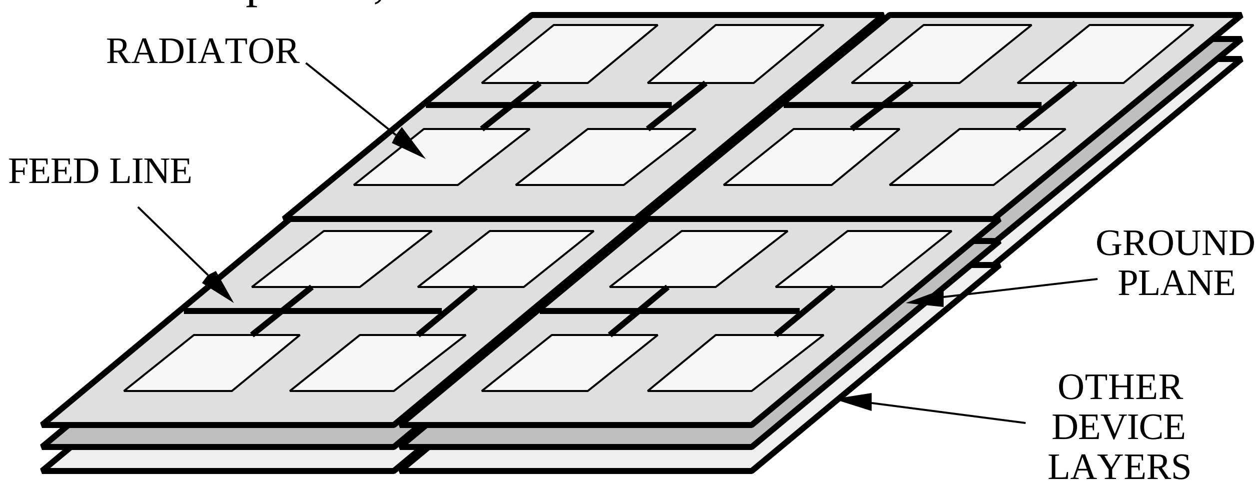
- Technology developed in late 70s and 80s is now common manufacturing technique

- Advantages:
  - ⇒ Potential low cost
  - ⇒ Improved reliability and reproducibility
  - ⇒ Compact and lightweight
  - ⇒ Broadband
  - ⇒ Design flexibility and multiple functions on a chip

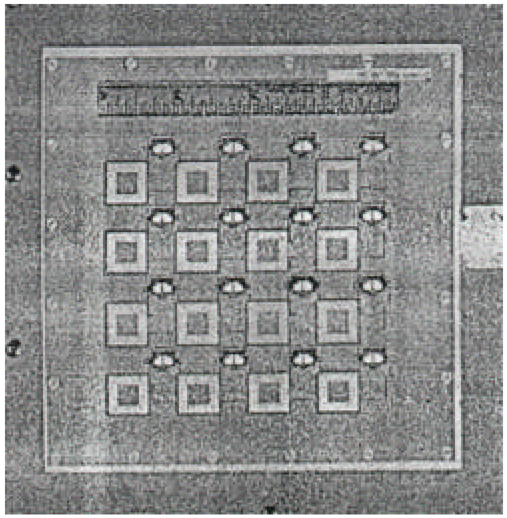
- Disadvantages:
  - ⇒ Unfavorable device/chip area ratios
  - ⇒ Circuit tuning not possible
  - ⇒ Troubleshooting a problem
  - ⇒ Coupling/EMC problems
  - ⇒ Difficulty in integrating high power sources

Tile Concept

- Low profile, conformal

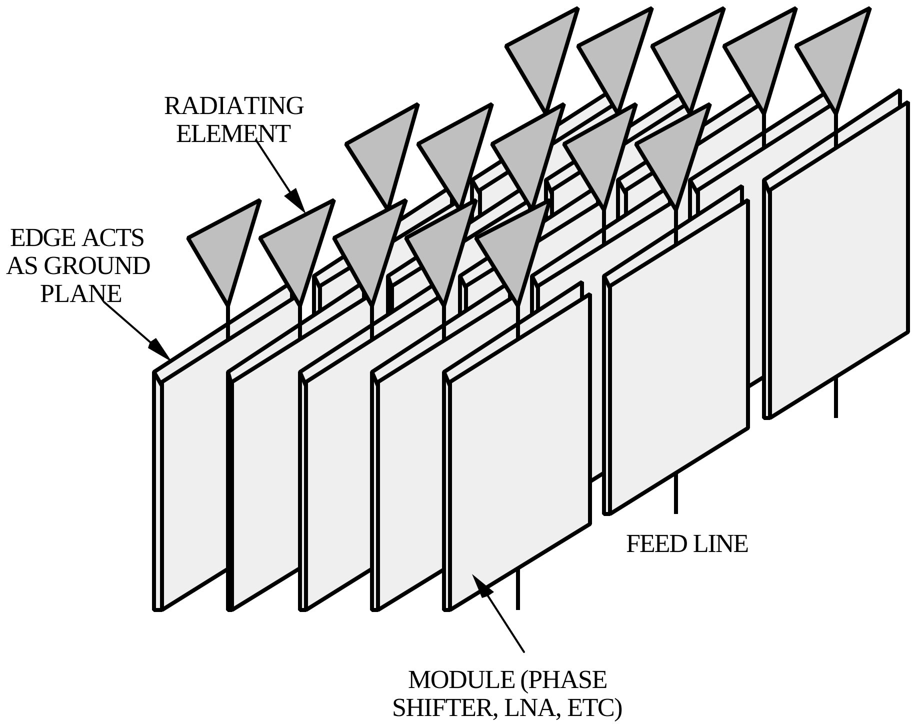


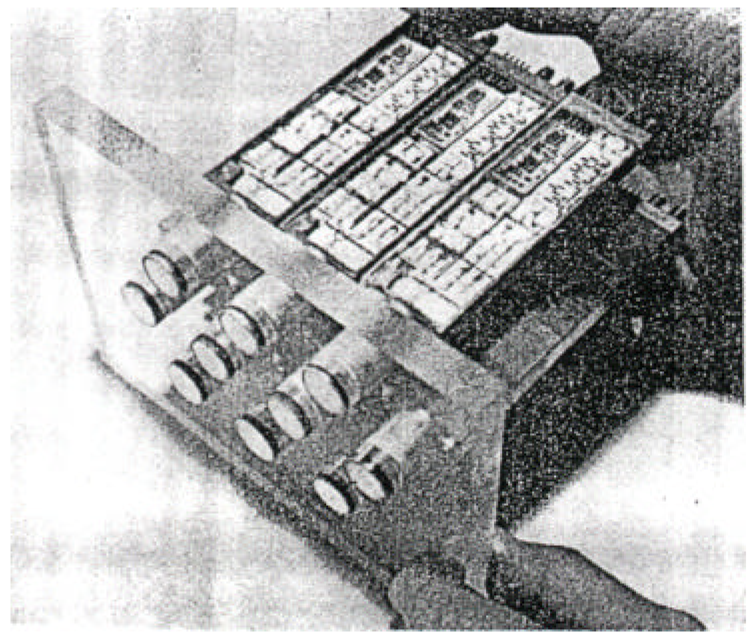
From paper by Gouker, Delisle and Duffy, IEEE Trans on MTT, vol 44, no. 11, Nov. 1996



Module Concept

- Independent control of each element





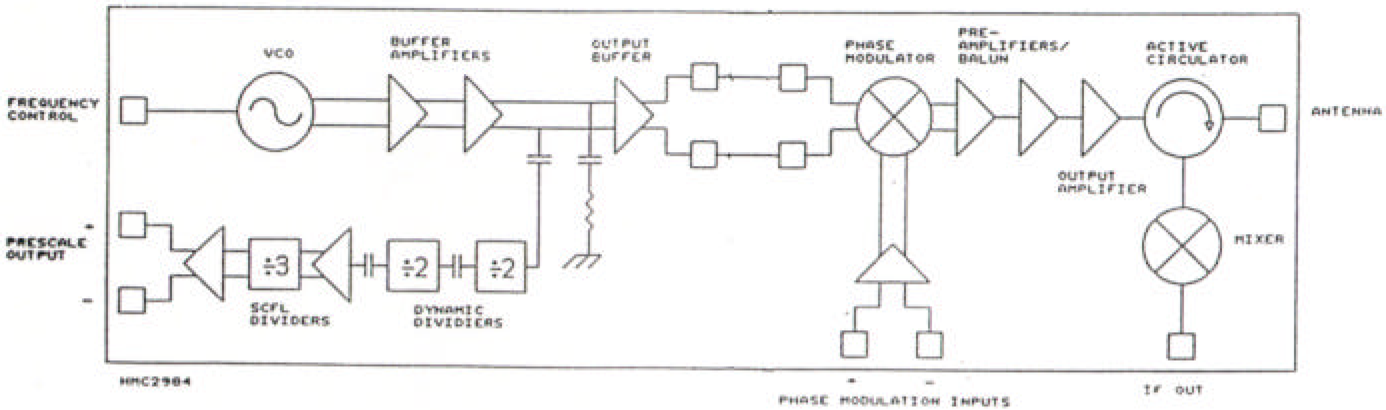
From Hughes Aircraft Co.

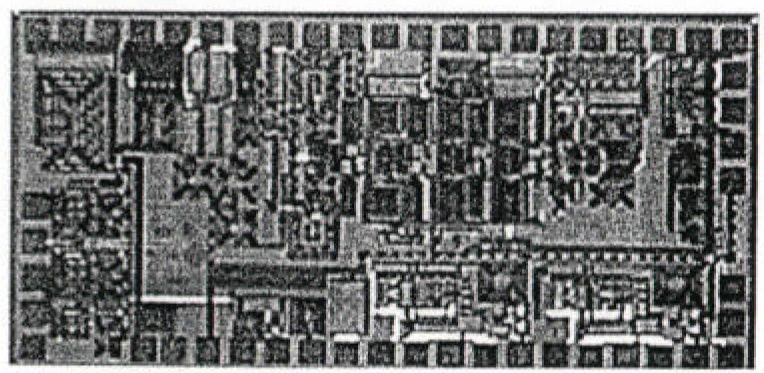
MMIC Single Chip Radar (1)

• Transmitter:	Frequency	5.136 GHz
	FM mod BW	50 MHz
	Output power	+17 dBm
• Phase modulation:	Code	BPSK
	Phase Accuracy	$\pm 2^\circ$
	Amp balance	± 0.5 dB
	Mod rate	50 MHz
	Switching speed	3 nsec
• Receiver:	3 dB BW	50 MHz
	Noise figure	30 dB, max
• Power supply:		5 VDC, 400 mA
• Temperature range:		-55° to 75°

Reference: "A MMIC Radar Chip for Use in Air-to-Air Missile Fuzing Applications," M Polman, et al, 1996 MTT International Symposium Digest, vol. 1, p. 253, 1996.

MMIC Single Chip Radar (2)





Reference: "A MMIC Radar Chip for Use in Air-to-Air Missile Fuzing Applications," M Polman, et al, 1996 MTT International Symposium Digest, vol. 1, p. 253, 1996.

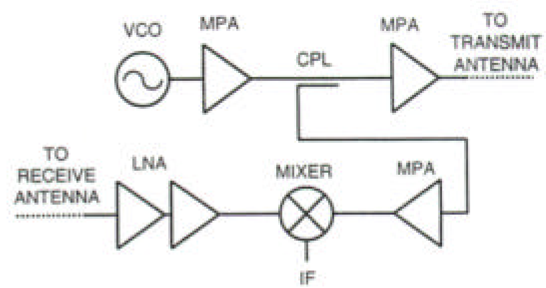
MMIC FMCW Single Chip Radar (1)

• Transmitter:	Frequency	94 GHz
	FM mod BW (Δf)	1 GHz
	Output power	5 mW
• MPA (Power amplifier):	Gain	6 dB
	1 dB compression point	7 to 8 dB
	Saturation power	12 to 13 dB
• LNA:	Gain	18 to 20 dB
	Noise figure	6 to 7 dB
• Coupler:	Coupling coefficient	10 dB
	Isolation	20 dB
	Return loss	20 dB
• Mixer:	Conversion gain	9 dB
	Noise figure	7.5 dB
	IF frequency	1.5 GHz

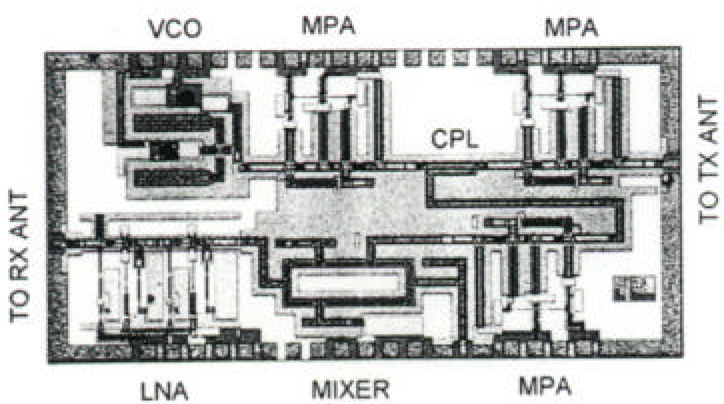
Reference: "Single Chip Coplanar 94-GHz FMCW Radar Sensors," W. Haydl, et al, IEEE Microwave and Guided Wave Letters, vol. 9, no. 2, February 1999.

MMIC FMCW Single Chip Radar (2)

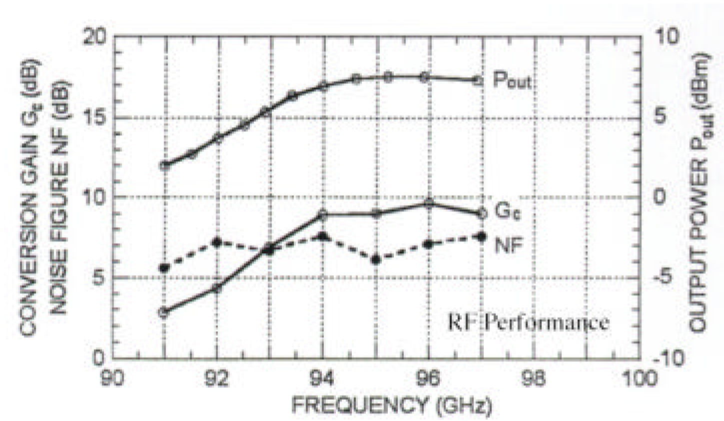
Reference: "Single Chip Coplanar 94-GHz FMCW Radar Sensors," W. Haydl, et al, IEEE Microwave and Guided Wave Letters, vol. 9, no. 2, February 1999.



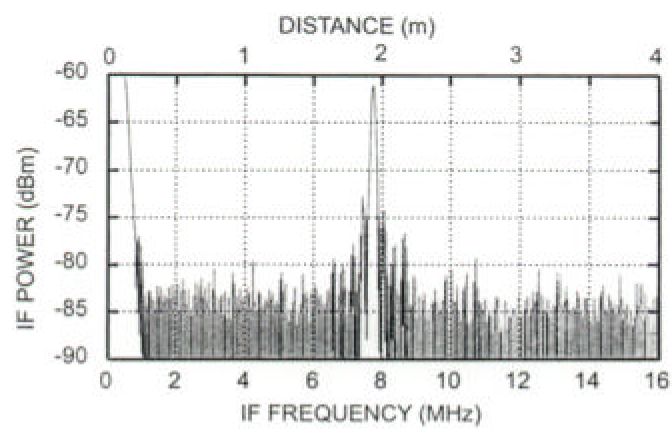
Block diagram of a 94-GHz FMCW sensor MMIC



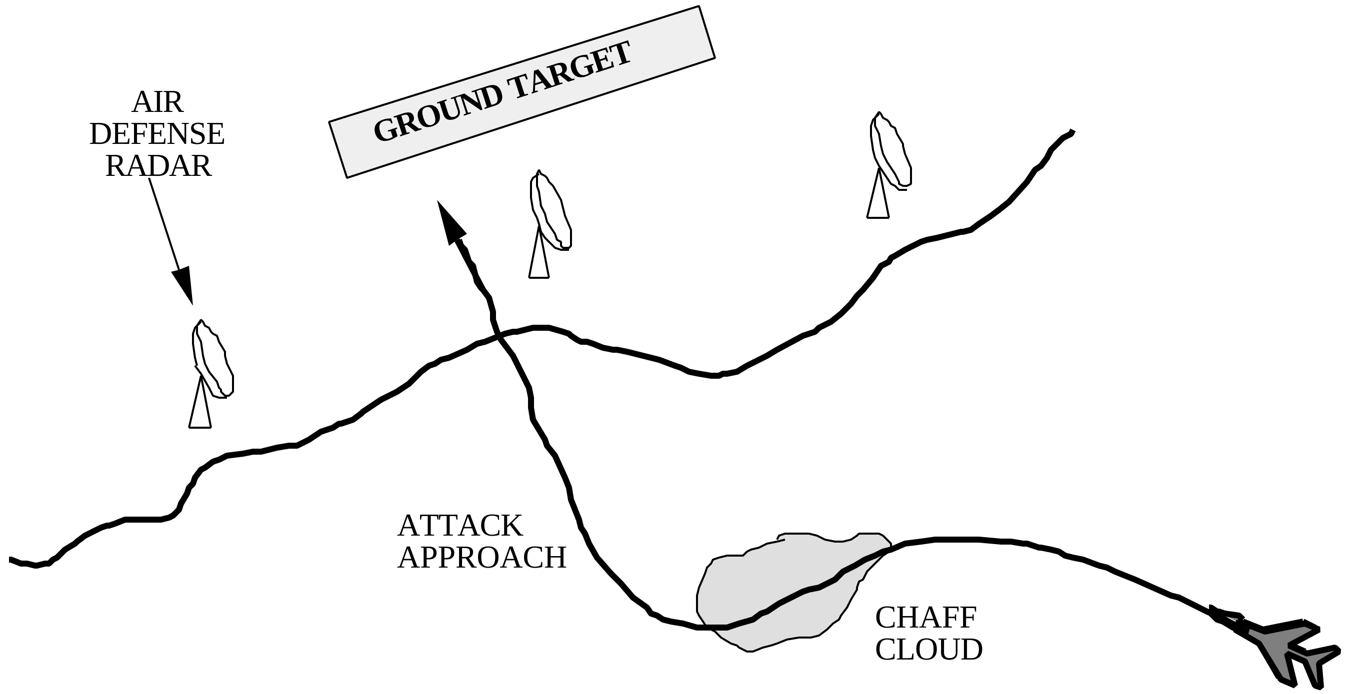
Actual chip size is 2 by 4 square mm



IF signal from a 1 square cm metal targe at 2 m (below)



Defeating Radar Using Chaff

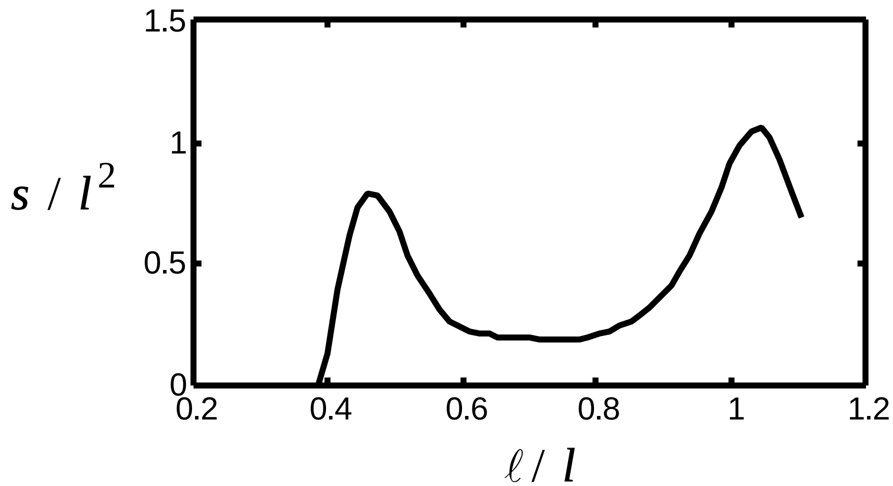


Chaff floods the radar with false targets.

The radar is aware of the intruder.

Chaff (1)

Chaff is a means of clutter enhancement. Common chaff consists of thousands of thin conductive strips. For a narrowband radar the strips are usually cut to the same length; one that corresponds to a resonance. The shortest resonant length is about $\ell = 0.45\lambda$ as shown below (the exact value depends on the dipole diameter, d).



After the aircraft discharges the chaff, it expands to form a cloud. In the cloud, the dipoles are usually modeled as uniformly distributed (uniform density) and randomly oriented. The dipole scattering pattern, where θ is measured from the dipole axis, is

$$\sigma(\theta) = \sigma_{\max} \sin^2(\theta)$$

Chaff (2)

Maximum broadside backscatter for a dipole is

$$s_{\max} = \frac{p^5 \ell^6}{16\, l^4 (\log(2\ell/d) - 1)^2}$$

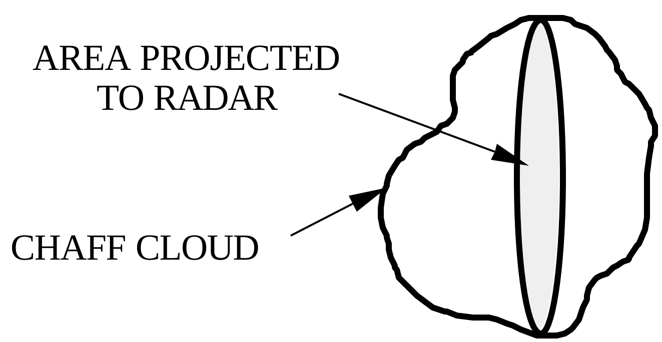
The average RCS over all angles is

$$\bar{s} = \iint s(q, f) \sin q \, dq \, df = \frac{2}{3} s_{\max}$$

An approximate value good for most calculations is $\bar{s} \approx 0.15\, l^2$. For a short time after the chaff has been discharged, the RCS of the chaff cloud can be approximated by

$$s \approx A_c \left(1 - e^{-n\bar{s}}\right)$$

where A_c is cross sectional area of the chaff cloud presented to the radar.



Chaff (3)

The number of dipoles in the projected plane is $n = N / A_c$, N being the total number of elements in the cloud. After the dipoles are widely dispersed n becomes small and

$$\overline{s}_c \approx A_c n \overline{s} = N \overline{s}$$

Example: Number of resonant dipoles required for an average cloud RCS of $\overline{s}_c = 20$ dBsm at a frequency of 2 GHz.

The average RCS for a dipole is $\overline{s} \approx 0.15\, l^2 = 0.0034$. Therefore the RCS of a cloud of randomly oriented dipoles (which is the case at late time) is

$$\overline{s}_c \approx N \overline{s} \Rightarrow N \approx 100 / 0.0034 = 29412$$

"Advanced" chaff designs:

1. Multiband chaff: bundles contain multiple resonant lengths
2. Absorbing chaff: resistive material absorbs rather than reflects

Chaff and Flares

F-16 dispensing chaff and flares (USAF photo)

Bistatic Radar (1)

Bistatic radars were among the first deployed radars. The German Klein Heidelberg radar of WW II used the British Chain Home radar as a transmitter. Receivers were located in Denmark and the Netherlands. It was capable of detecting a B-17 at 280 miles. Bistatic gave way to monostatic because of several factors:

- excessive complexity
- high costs and other solutions competing for $
- degraded performance relative to a monostatic radar
    - -- reduced range and angles
    - -- limited engagement capability
    - -- degraded range and doppler resolution
- limited data and field tests
- threats insignificant
- monostatic mindset

Unique aspects and challenges of bistatic radar include:

- difficulty in measuring range
- efficient search and dealing with "pulse chasing"
- synchronization of the transmitter and receiver
- a significant advantage against stealth targets: forward scattering

Bistatic Radar (2)

Hitchhiker radars systems do not have their own transmitters, but use "transmitters of opportunity" which include

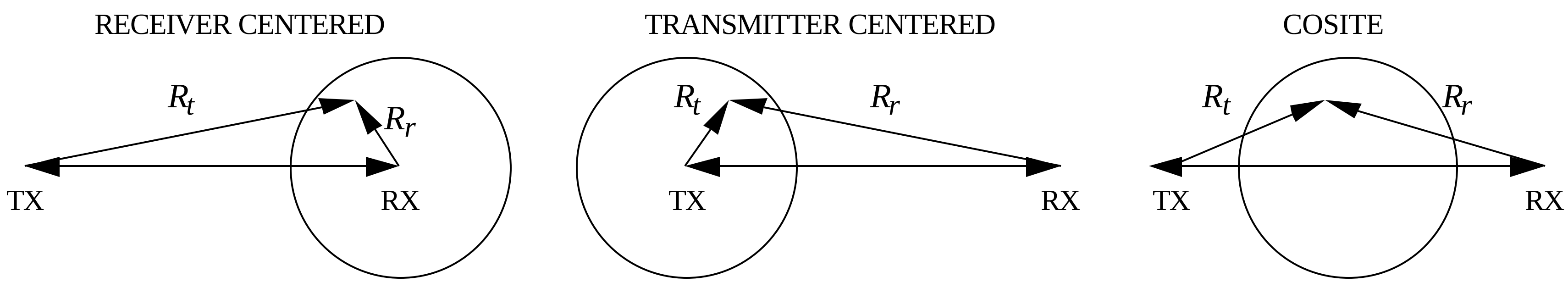
- other radars (military or civilian)
- commercial transmitters (televisions stations, etc.)
- may be cooperative or non-cooperative

Echoes from targets are received and processed by the hitchhiker radar

- limited ranges and engagement
- degraded performance, especially for non-cooperative transmitters

Special cases:

- $R_t >> R_r$: receiver centered (standoff TX with RX on penetrating aircraft)
- $R_r >> R_t$: transmitter centered (missile launch alert)
- cosite (trip-wire fences; satellite tracking from ground sites)



FLIGHT-TRACKING FIRM TAKES OFF

BY MATTHEW L. WALD
New York Times

BOHEMIA, N.Y.

THE FIERY ending of TWA Flight 800 cast a harsh light into various corners of the aviation business. But some key data for investigating the disaster came from a tiny industry niche in Bohemia that the National Transportation Safety Board never knew existed.

The morning after the July 17 disaster, John R. Keller called directory assistance and asked for the New York City headquarters of the FBI. "I have a radar map of the accident," Keller told the agent who answered the phone.

Keller is executive vice president of Megadata Corp., which was able to provide air-traffic records more quickly and completely than the Federal Aviation Administration of the seconds before and after the Paris-bound Boeing 747 disappeared from radar screens.

THE DATA helped investigators determine which other aircraft in the vicinity had the clearest eyewitness view of the disaster and its immediate aftermath.

Tiny Megadata's role in the investigation highlights a chink in air-to-ground communications that is not widely recognized by the public but is apparent enough to some airline and airport officials, and the company has been able to make a business of plugging the gap.

Clients include United Airlines, which uses Megadata's technology to coordinate ground crews in five cities during the last few minutes of incoming flights — a period when the FAA limits communications with planes to essential conversations between cockpit and controllers.

Other Megadata customers include airports — including San Francisco International — whose managers need to know which planes were where and when if disputes arise over noise-abatement violations and the like.

In essence, Megadata, based in an industrial park near Long Island MacArthur Airport, produces a $250,000 system that eavesdrops on radio transmissions between the FAA and commercial airplanes.

Using computers and software more advanced than anything available to federal air controllers, the Megadata system massages information and converts it to an instant, real-time view of all aircraft aloft and their flight paths within a 150-mile radius. The setup maintains a database of this information and is able to instantly reproduce air-traffic records that might take the FAA days or weeks to compile.

"It's a completely clandestine operation; they don't even know we're there," said George B. Litchford, an engineer who holds the system's patent.

Litchford has been licensing the technology to Megadata since 1989. Megadata is thought to be the only company in this business so far, but it is hardly a gold-mine business.

MEGADATA, WHOSE stock is thinly traded on the OTC Bulletin Board, has revenues of less than $2 million a year from a range of communications products, and it lost money last year. The shares closed at 50 cents Wednesday, down 37.5 cents each, after spiking upward Tuesday on word of the company's involvement in the plane-crash investigation.

Although the National Transportation Safety Board was unaware of Megadata's existence before the crash, the FAA has known about the company but has ignored it.

Megadata's services may be useful to airlines for efficiently moving people on the ground, said Bill Jeffers, the FAA's director of air traffic. But "it doesn't have to do with the safe and efficient movement of aircraft," which Jeffers said was his agency's concern.

Yet, in the case of the TWA crash, Megadata's records proved invaluable to federal officials.

After Keller's phone call, safety board investigators and FBI agents went to Megadata's office to view charts and determine what other aircraft were in position to see the final moments of Flight 800.

Eyewitness reports are considered by aviation experts to be extremely unreliable, and the Megadata information helped establish whether the other pilots were in positions to see what they claimed to see.

Based on FAA radar scans that emanated from Riverhead, Megadata's charts indicated that two aircraft — an Army Black Hawk helicopter and an Air National Guard C-130 cargo plane — were indeed in position to have observed the fireball.

FAA radar systems of the type used in Riverhead send out pulses of energy that are reflected off metal objects in the sky, making blips on a screen. The systems also send out electronic queries, asking the identity and altitude of planes with on-board transponders — special radios that can respond to the FAA queries by emitting electronic identification codes one one-millionth of a second later.

SUBTRACTING THAT microsecond and dividing by the speed of light, the FAA knows the range, or how far away the plane is. By keeping track of precisely where the circular-scan radar beam is pointed when it asks the question, the FAA knows the direction, or bearing, of the aircraft.

Megadata's system simply eavesdrops. The main components are a receive-only antenna, about 5 feet high, which can be miles from the nearest airport, and a work station to process the data.

United Airlines has become Megadata's largest client, using the systems in Chicago, Denver, San Francisco, Los Angeles and at Dulles International Airport, near Washington, D.C.

Airport managers use Megadata's information mostly to enforce noise-abatement ordinances.

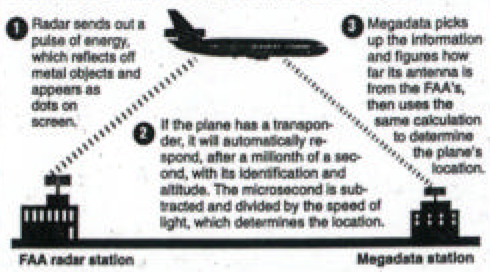
"We get complaints all the time," said Ron Wilson, a representative for San Francisco International Airport, which has used the Megadata system to resolve hundreds of complaints in the past few years.

'PEOPLE SAY: 'I saw a 747 come over my house at 500 feet. I know it was 500 feet because I could see the pilots. I could read the numbers. I could see the wheels.' "

Using the Megadata work station, Wilson said, airport officials could enter the location and the time to quickly determine the facts. "We can tell them, it wasn't 500 feet — it was 3,500 feet."

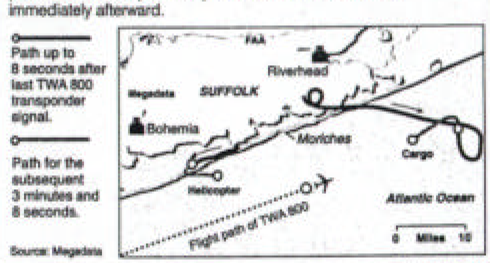
Radar Forensics

Technology from the Megadata Corporation helps airlines fill gaps in air-to-ground communications by monitoring FAA radar and quickly reprocessing the data. Megadata's information has helped investigators determine which other aircraft were truly in a position to witness the crash of TWA Flight 800. Here is how the system works:



What Megadata Recorded During the Crash

Megadata recorded the final path of Flight 800 and the flight paths of two military aircraft just before the disaster, and immediately afterward.



NEW YORK TIMES

Bistatic Radar (3)

<u>"Rabbit Ear" Radar</u>

Once upon a time people had rabbit ear antennas on their televisions. Over a relatively wide area around airports, e.g., LAX or SFO, almost every aircraft takeoff caused interference with the TV. This is the same situation as a bistatic hitchhiker radar:

- transmitter is the local TV station
- receiver is your TV set

The picture flutter and snow are due mainly to a mix of forward scattering and direct path signals

<u>Bistatic Alert and Cueing (BAC)</u>

- for passive situational awareness (PSA)
- standoff aircraft such as an AWACS is used as an transmitter /illuminator
- multiple dispersed receivers are used
- important issues include bistatic clutter, ECM and cost

<u>Multistatic Radar</u>

- two or more receivers with common or overlapping spatial coverage
- data is combined at a common location
- usually noncoherent (example: Space Surveillance System)
- when combined coherently, the radar net is equivalent to a large baseline array

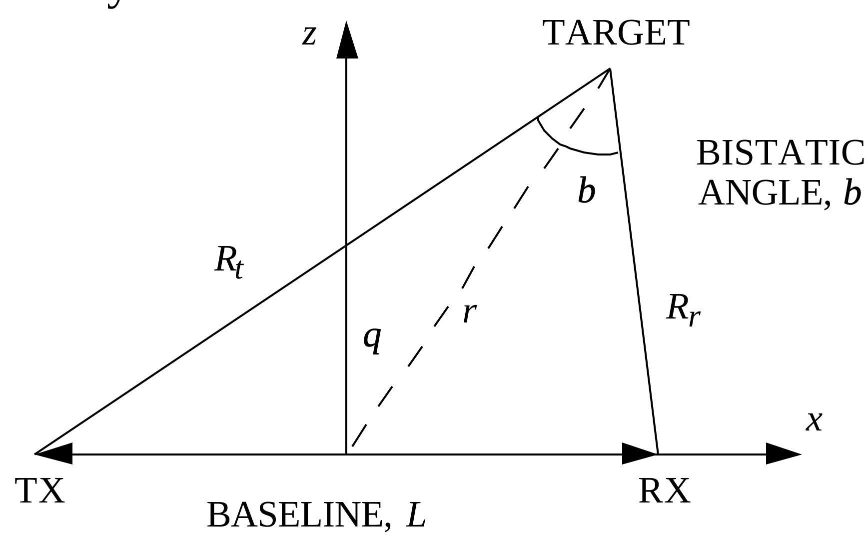
Bistatic Radar (4)

Bistatic radar range equation:

$$(R_r R_t)_{\max} = \left[\frac{P_t G_t G_r\, l^2 s_B F_t^2 F_r^2 G_p}{(4p)^3 k \mathrm{T}_s B_n (S/N)_{\min} L_t L_r} \right]^{\frac{1}{2}}$$

s_B = bistatic RCS
F_t, F_r = transmit and receive path gain factors
L_t, L_r = transmit and receive losses

Radar and target geometry:



Bistatic Radar Example

Example: A buoy is dropped in the center of a 1 km wide channel to detect passing ships. A 1 W transmitter on the buoy operates at 1 GHz with a 0 dBi antenna. The receiver is located on an aircraft flying directly overhead. The receiver MDS is –130 dBW and the antenna on the aircraft has a 20 dBi gain.

(a) What is the maximum range of the receive aircraft if the ship RCS is 30 dB? Neglect losses and multipath.

Assume that the ship is as far from the buoy as possible and that the receive antenna beam is pointed directly at the ship

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma_B}{(4\pi)^3 R_r^2 R_t^2} = \frac{(1)(100)(1)(1000)(0.3^2)}{(4\pi)^3 (10^3)^2 R_r^2} = 10^{-13} \Rightarrow R_r = 6735\,\mathrm{m}$$

(b) If the aircraft had a monostatic radar, what would be the required transmitter power?

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} = 10^{-13} \Rightarrow P_t = 0.45\,\mathrm{W}$$

The increase in transmitter antenna gain in the monostatic case more than makes up for the monostatic R^4 factor.

Bistatic Radar (5)

Define the bistatic radar parameter, K, and the bistatic maximum range product, κ:

$$(R_r R_t)^2_{\max} = \kappa^2 = \frac{K}{(S/N)_{\min}} \quad \text{where} \quad K = \frac{P_t G_t G_r \lambda^2 \sigma_B F_t^2 F_r^2 G_p}{(4\pi)^3 k T_s B_n L_t L_r}$$

Constant SNR contours in polar coordinates are <u>Ovals of Cassini</u>

$$(R_r R_t)^2 = (r^2 + L^2/4)^2 - r^2 L^2 \cos^2\theta$$

$$S/N = \frac{K}{(r^2 + L^2/4)^2 - r^2 L^2 \cos^2\theta}$$

Operating regions:

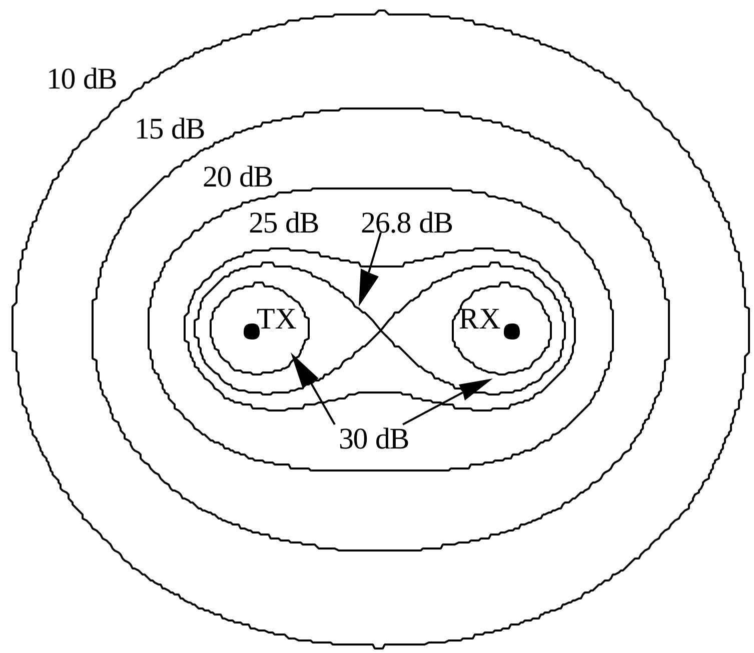
- $L > 2\sqrt{\kappa}$, two separate ellipses enclosing the transmitter and receiver
- $L < 2\sqrt{\kappa}$, a single continuous ellipse (semimajor axis b; semiminor axis a)

$$a = \left(R_t + R_r\right)/2 \quad b = \sqrt{a^2 - (L/2)^2} \quad e = \frac{L}{R_t + R_r} = \frac{L}{2a}$$

- $L = 2\sqrt{\kappa}$, lemniscate with a cusp at origin

Bistatic Radar (6)

Example: constant SNR contours for $K = 30L^4$ ("Ovals of Cassini")



Special cases: receiver centered ($L > 2\sqrt{k}$, $R_t >> R_r$), transmitter centered ($L > 2\sqrt{k}$, $R_r >> R_t$), cosite region ($L < 2\sqrt{k}$). The maximum SNR occurs at $b = 0$ and has a value $(SNR)_{\max} = K / b^4$. The minimum SNR occurs at the maximum bistatic angle (along the baseline perpendicular) and has the value $(SNR)_{\min} = K\left(1 + \cos(2\sin^{-1}(e)\right)^2 /(4b^4)$.

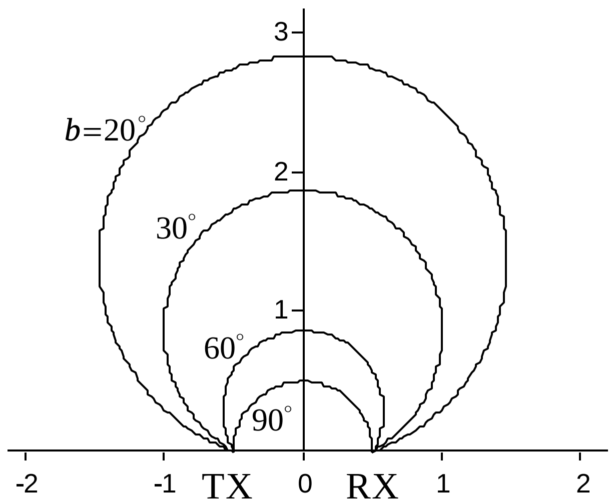
Bistatic Radar (7)

Bistatic radar operation is often limited or constrained by the maximum or minimum bistatic angle. Contours of constant bistatic angle, b, are circles of radius

$$r_b = L/(2\sin b)$$

centered on the baseline bisector at

$$d_b = L/(2\tan b)$$



The dimensions are distance normalized by baseline, L

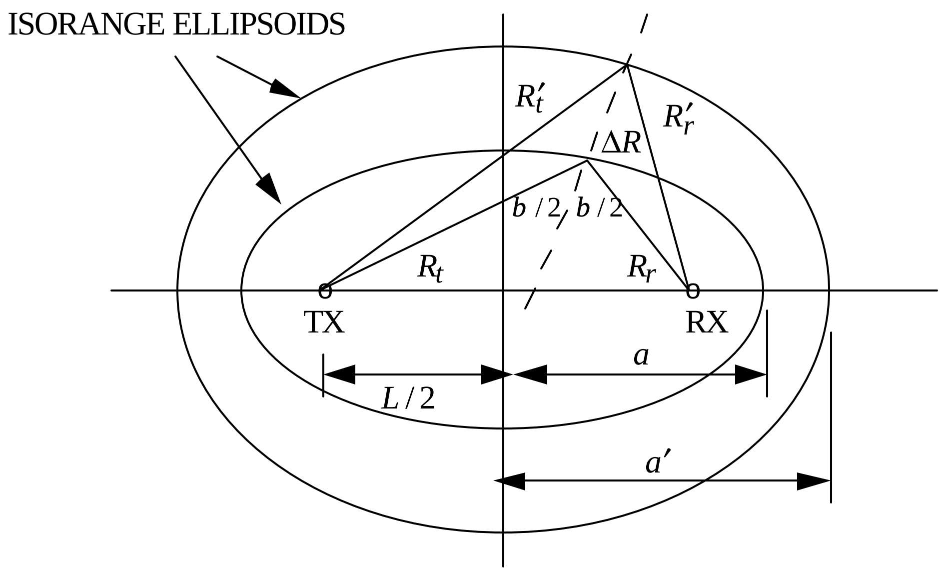
Bistatic Radar (8)

Bistatic range cells are defined by ellipsoids $R_t + R_r = 2a$. The range cell size is approximately given by

$$\Delta R \approx \frac{\Delta R_{\max}}{\cos(b/2)} = \frac{ct}{2\cos(b/2)}$$

The maximum error occurs along the perpendicular bisector and is given by

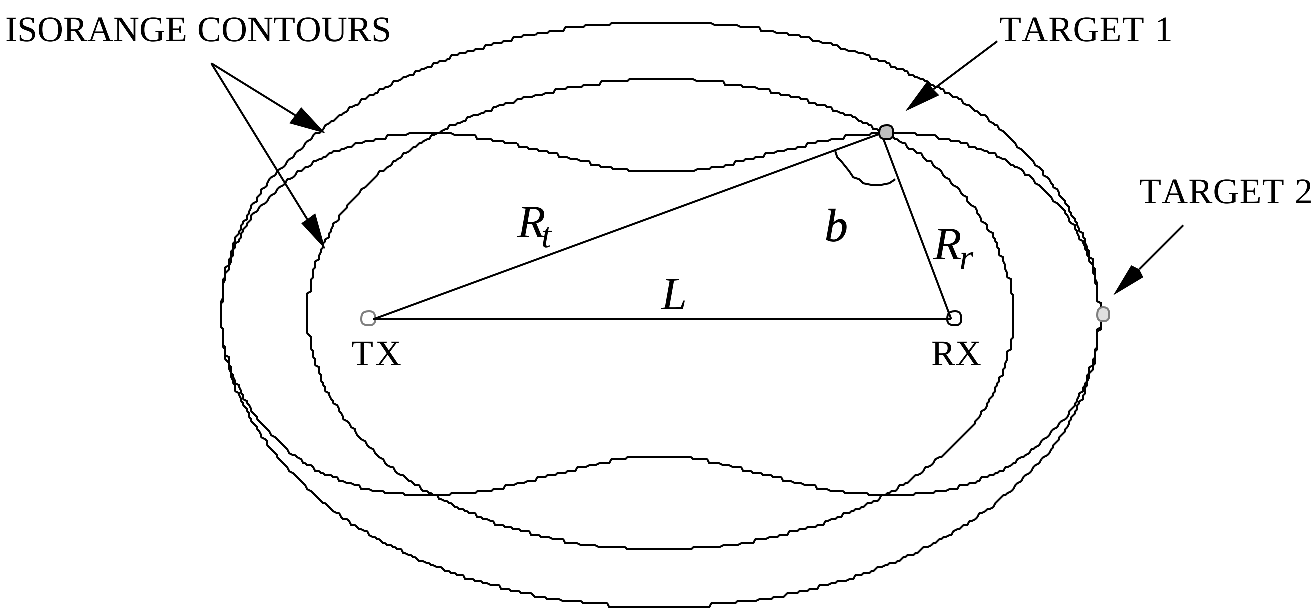
$$d_{\max} \approx \frac{a(a' - a)}{b(b' - b)} - 1 \text{ where } b = \left(a^2 - (L/2)^2\right)^{1/2} \text{ and } b' = \left((a')^2 - (L/2)^2\right)^{1/2}$$



Bistatic Radar (9)

A family of isorange contours is associated with each Oval of Cassini (contour of constant $(S/N)_{\min}$). Both equations are satisfied by the same bistatic angle, b, yielding the equation

$$(R_t + R_r)_{\max} = \left[L^2 + 2(\underbrace{R_t R_r}_{k})_{\max}(1 + \cos b) \right]^{1/2}$$



The SNR is different for targets at various locations on an isorange contour.

Bistatic Radar (10)

Target location can be computed if the time delay of the scattered pulse is referenced to the transmission delay directly from the transmitter

$$(R_t + R_t) = c\Delta T_L + L$$

where ΔT_L is the time difference between reception of the echo and the direct pulse

Unambiguous range is given by $(R_t + R_t)_u = c / f_p$ which describes an ellipse with semimajor axis of length c / f_p.

Target velocity is computed from the doppler shift, which in the bistatic case is given by

$$f_d = \frac{1}{l}\left[\frac{d}{dt}(R_t + R_r)\right] = \frac{1}{l}\left[\frac{dR_t}{dt} + \frac{dR_r}{dt}\right] = \frac{2v_t}{l}\cos d \cos(b/2)$$

$\frac{dR_t}{dt}$ = the projection of the target velocity vector onto the transmitter-to-target LOS

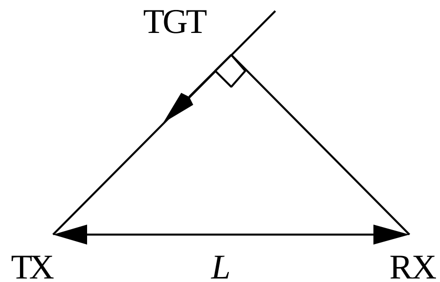
$\frac{dR_r}{dt}$ = the projection of the target velocity vector onto the receiver-to-target LOS

v_t = the target velocity projected onto the bistatic plane

d = angle between target velocity vector and the bistatic angle bisector

Bistatic Radar Example

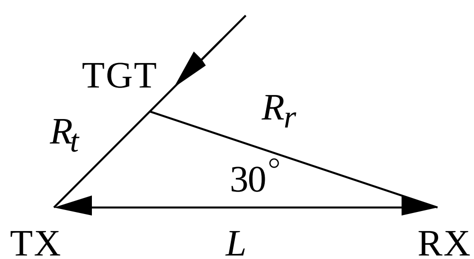
(a) A target is approaching the transmitter at 100 m/s. What is the doppler shift when the target location on its approach is perpendicular to the receiver line of sight?



$$\frac{dR_t}{dt} = |\vec{v}| = 100\,\text{m/s}, \quad \frac{dR_r}{dt} = 0$$

$$f_d = \frac{1}{l}\left[\frac{dR_t}{dt} + \frac{dR_r}{dt}\right] = \frac{v}{l} = \frac{100}{0.1} = 1000\,\text{Hz}$$

(b) The echo from the target arrives $\Delta T_L = 200\ m\text{s}$ after the direct transmission. The receive antenna beam is 30 degrees from the baseline. Find the target ranges to the transmitter and receiver if the baseline is 30 km.



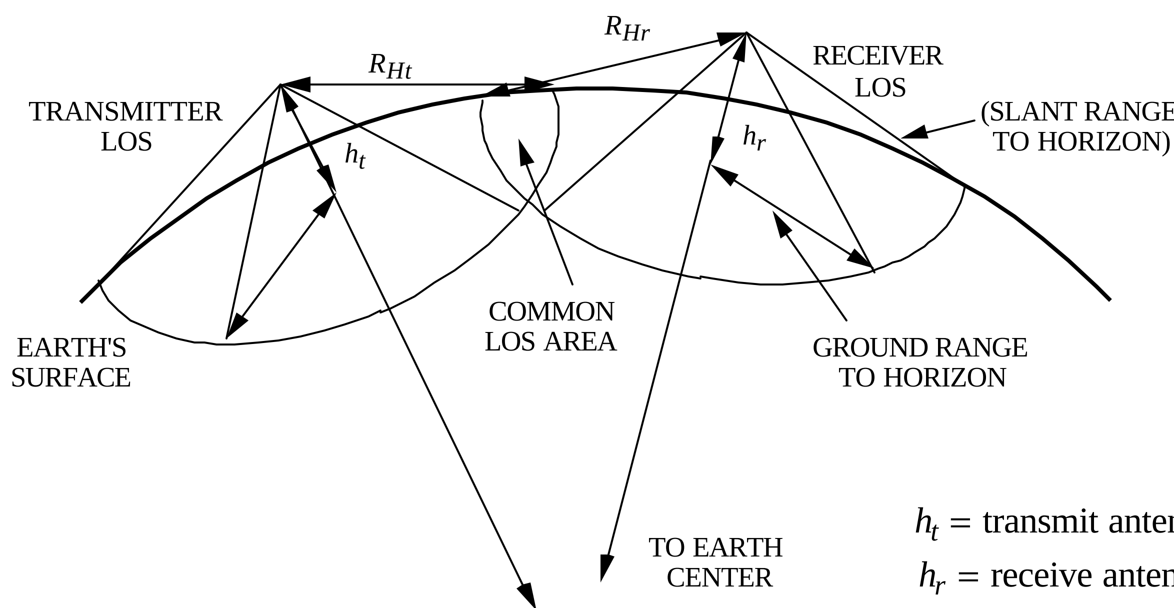
$$R_t^2 = R_r^2 + L^2 - 2R_r L\cos(30^\circ)$$

$$(R_t + R_r) = c\Delta T_L + L$$

Solve the two equations for the ranges: $R_r = 56.23$ km and $R_t = 33.76$ km

Line-of-Sight Constrained Coverage (1)

Both the transmitter and receiver must have line of sight (LOS) to the target. Example of overlapping LOS coverage for a bistatic radar for a target height of zero:



h_t = transmit antenna height

h_r = receive antenna height

h_{tgt} = target height

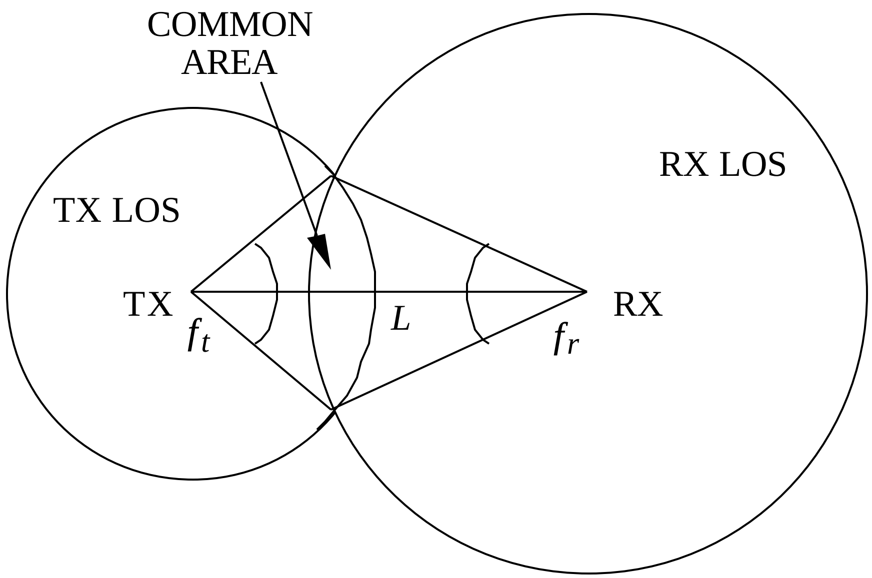
$$R_{Ht} \approx 130\sqrt{h_t + h_{tgt}} \text{ km}$$

$$R_{Hr} \approx 130\sqrt{h_r + h_{tgt}} \text{ km}$$

$L \le 130\sqrt{h_t + h_r}$ km for direct transmission from TX to RX

Line-of-Sight Constrained Coverage (2)

Top view of overlapping coverage



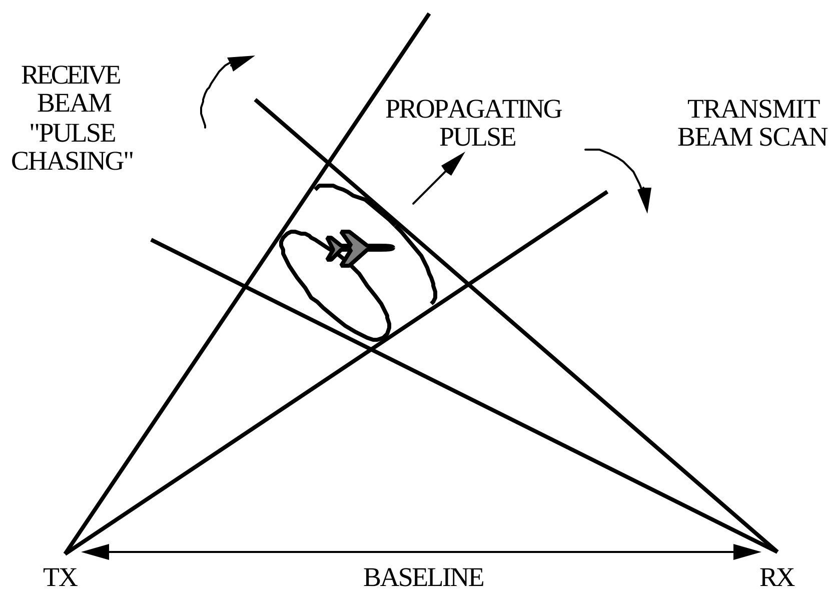
Common area: $A_o = \frac{1}{2}\left[R_{Hr}^2(f_r - \sin f_r) + R_{Ht}^2(f_t - \sin f_t)\right]$

where $f_t = 2\cos^{-1}\left[\frac{R_{Ht}^2 - R_{Hr}^2 + L^2}{2R_{Ht}L}\right]$ and $f_r = 2\cos^{-1}\left[\frac{R_{Hr}^2 - R_{Ht}^2 + L^2}{2R_{Hr}L}\right]$. The equation holds for $L + R_{Hr} \le R_{Ht} \le L + R_{Hr}$ or $L + R_{Ht} \le R_{Hr} \le L + R_{Ht}$ (one circle does not completely overlap the other).

Bistatic Radar (11)

Detection of a target requires that the target be in both the transmit and receive beams as the pulse illuminates the target. This is referred to as <u>beam scan on scan</u>, and it can be accomplished in four ways:

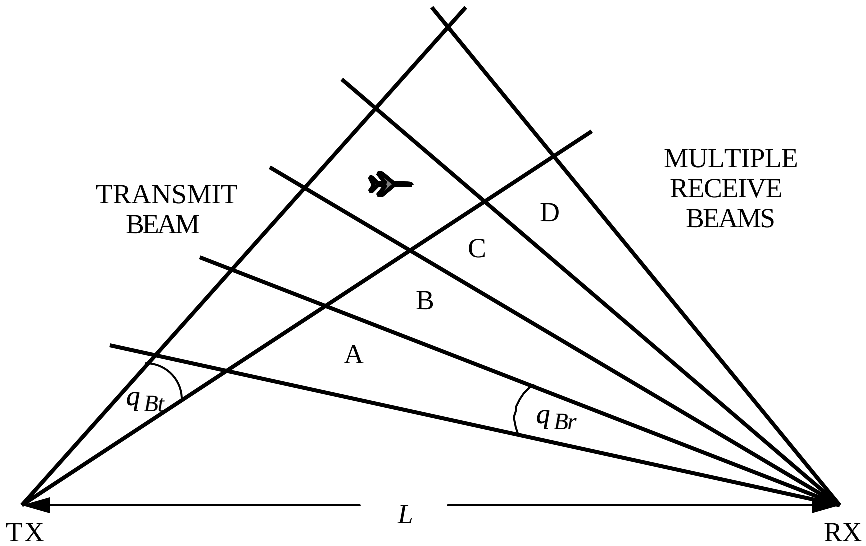
1. One high gain beam on transmit and one high gain beam on receive. This requires that the receive beam follow the pulse as it propagates through space (<u>pulse chasing</u>)



- Requires very fast receive beam scanning capability (implies an electronically scanned phased array)
- Time consuming for search

Bistatic Radar (12)

2. One high gain beam on transmit and multiple high gain beams on receive.



- Complex receive array required
- Rapid search of large volumes
- Only process range cells illuminated by the transmit beam

3. Floodlight transmit ($\Omega_{At} = \Omega_s$) with high gain receive beam

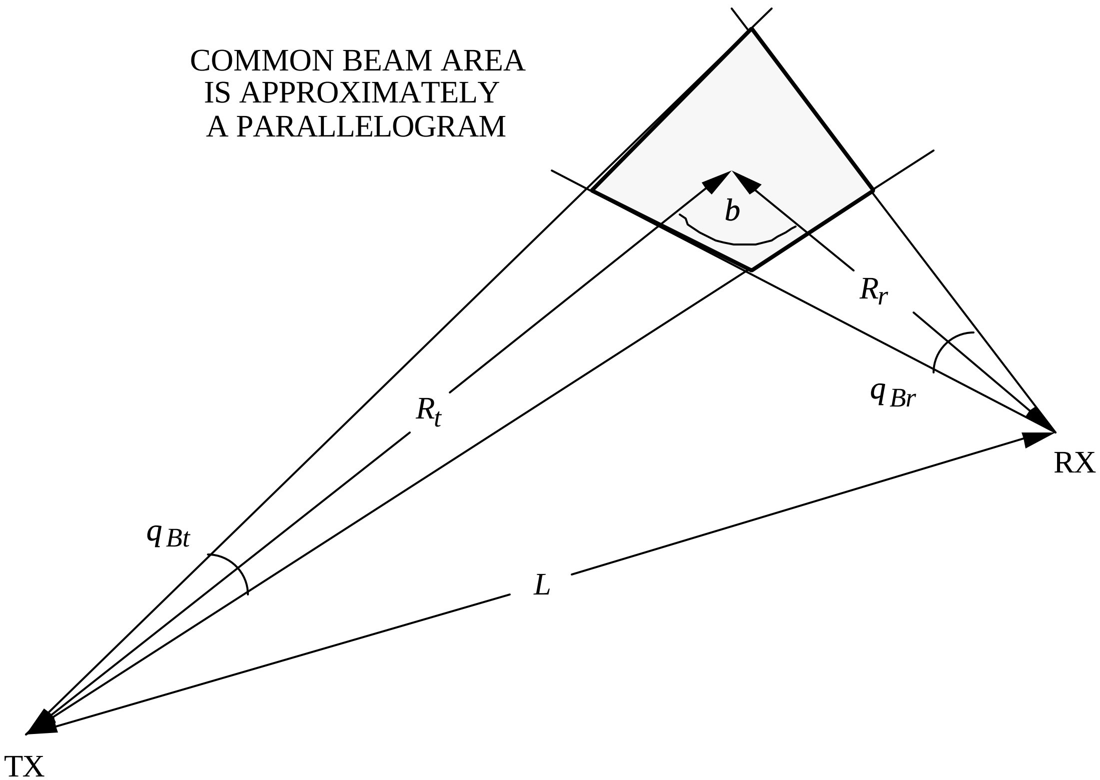
4. High gain transmit beam with floodlight receive beam ($\Omega_{Ar} = \Omega_s$)

The last two approaches are not normally used because

- Mainbeam clutter large
- Angle accuracy low

Bistatic Footprint and Clutter Area (1)

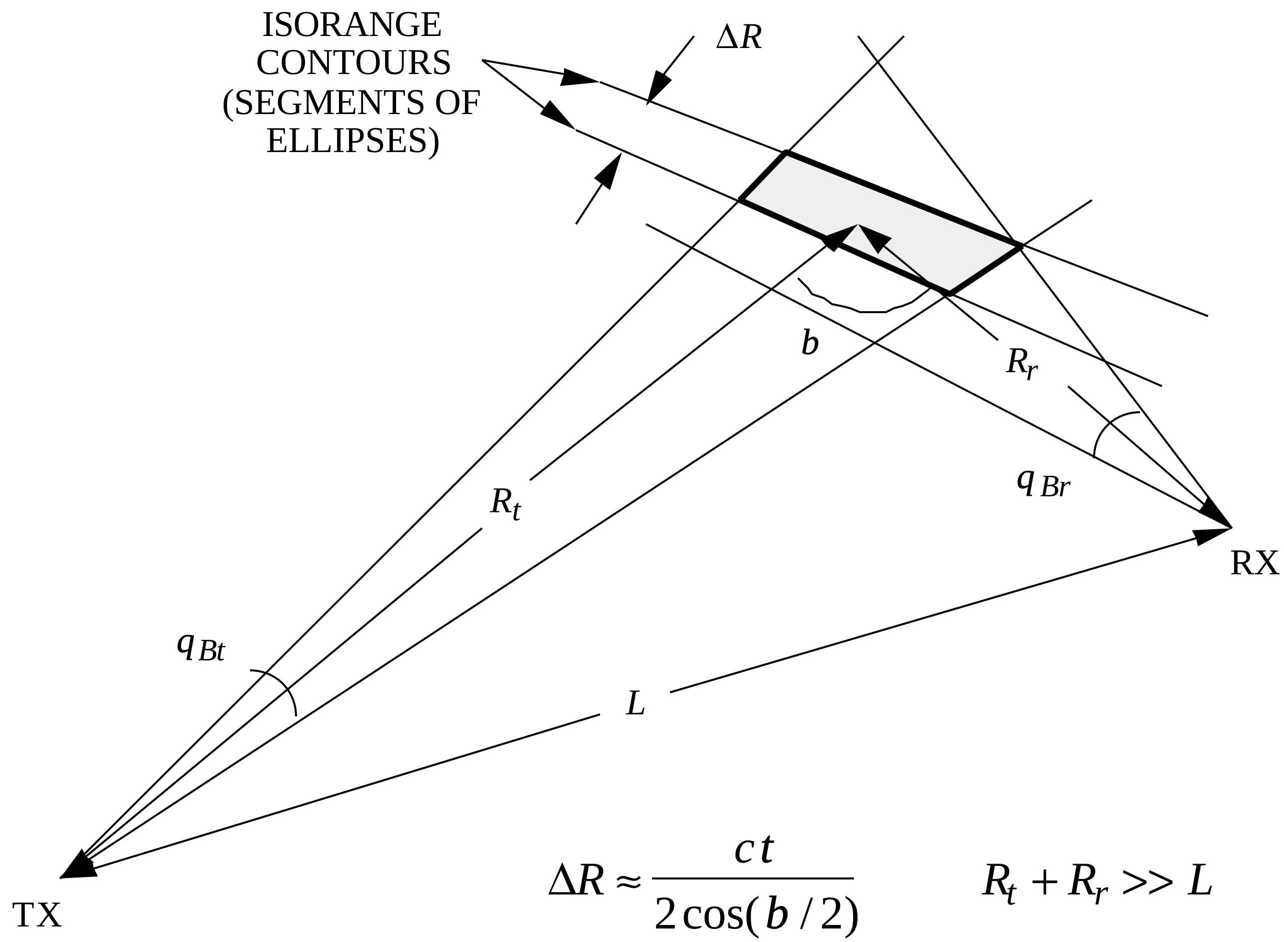
Simple antenna beam model: 1) constant gain within the HPBW, zero outside, and 2) circular arcs are approximately straight lines. Example of bistatic footprint (for small grazing angles and $R_t + R_r >> L$):



1. Beamwidth limited: (entire shaded area) $A_c \approx \dfrac{(R_r q_{Br})(R_t q_{Bt})}{\sin b}$

Bistatic Footprint and Clutter Area (2)

2. Pulsewidth (range) limited: $A_c \approx \Delta R \dfrac{(R_r \theta_{Br})}{\cos(\beta/2)} = \dfrac{c\tau R_r \theta_{Br}}{2\cos^2(\beta/2)}$



$$\Delta R \approx \frac{c\tau}{2\cos(\beta/2)} \qquad R_t + R_r >> L$$

Bistatic Radar Cross Section (1)

- Bistatic RCS is characterized by large forward scatter, particularly in the optical region
- The strength of the forward scatter depends on the target size and shape, aspect angle, frequency, and polarization
- For $b \approx 180^\circ$ the radar can only detect the presence of a target between the transmitter and receiver. The range is indeterminate (due to eclipsing of the direct pulse by the scattered pulse) and the doppler is zero
- Babinet's principle can be used to compute the forward scatter

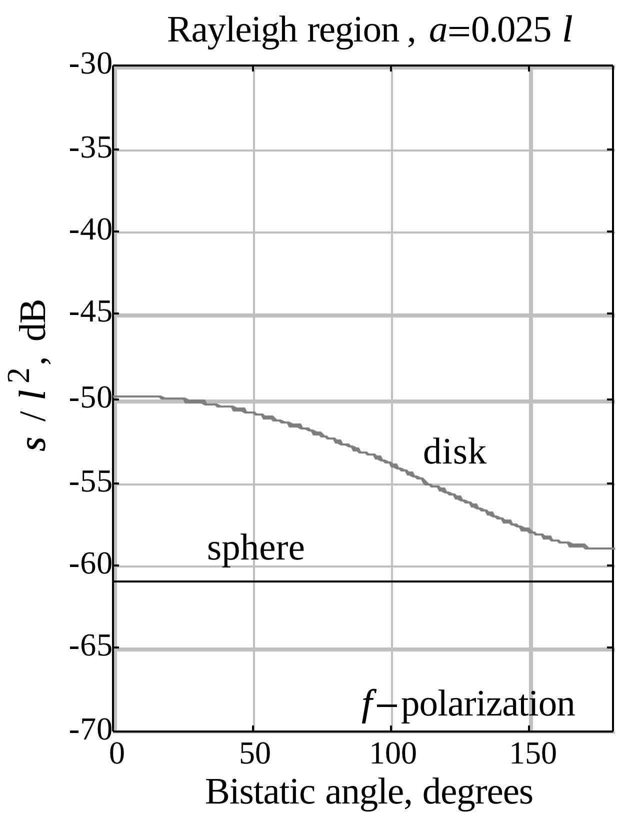
Example: A 2 m by 5 m rectangular plate at $l = 1$ m and $b \approx 180^\circ$ has a forward scatter RCS of approximately

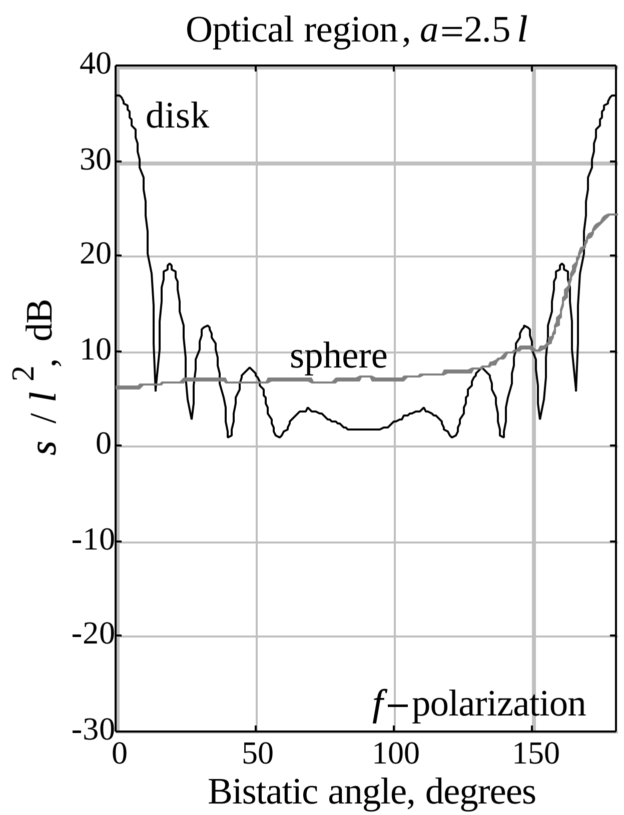
$$s_F \approx \frac{4p A^2}{l^2} = 1260 \text{ m}^2$$

If the radar can detect 5 m^2 targets, then the detection threshold is exceeded out the fourth sidelobe of the sinc pattern (40° from the forward scatter maximum). This corresponds to a bistatic angle of $b \approx 140^\circ$. The forward scatter HPBW is approximately $l/2$ by $l/5$ radians (23° by 11°).

Bistatic Radar Cross Section (2)

Comparison of the bistatic RCS of spheres and disks of the same diameter ($\phi_i = 0^\circ$)





Bistatic Radar Example Revisited

Example: Returning to the previous example regarding a buoy that is dropped in the center of the channel to detect passing ships. Compare the transmit power for the bistatic and monostatic cases if the bistatic RCS is 10 dB higher that the monostatic RCS.

For an altitude (range) of 6735 m the monostatic radar required $P_t = 0.45\,\mathrm{W}$ assuming that the monostatic and bistatic cross sections are the same. If the bistatic RCS is increased by 10 dB then the buoy transmitting power can be reduced by 10 dB, or

$$P_t = 0.1\ \mathrm{W}$$

Comments:

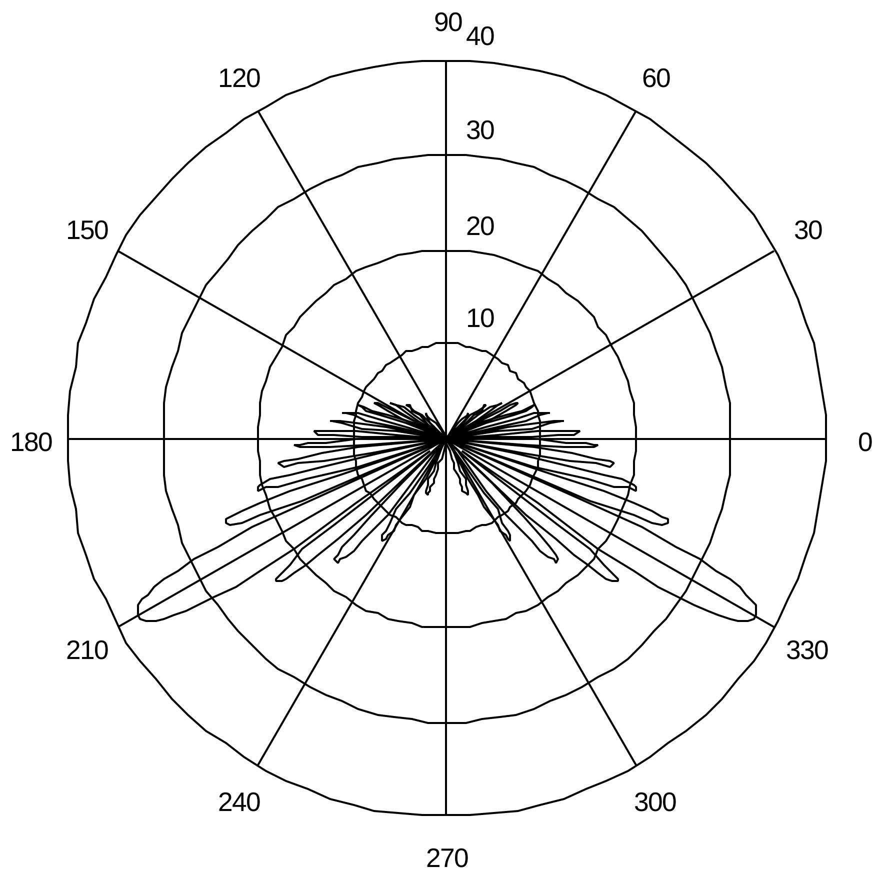
1. One advantage of the bistatic radar is that the aircraft position is not given away

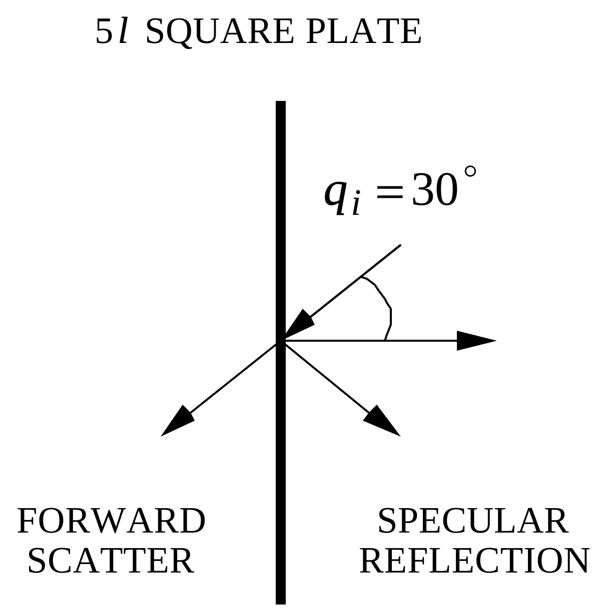
2. Achieving a 10 dB RCS advantage would probably require a limited engagement geometry that puts the receiver aircraft in the target's forward scatter beam. This would be difficult to insure with a ground based transmitter and an airborne receiver.

3. The receiver dynamic range and pulse timing may be a problem

Bistatic Radar Cross Section (3)

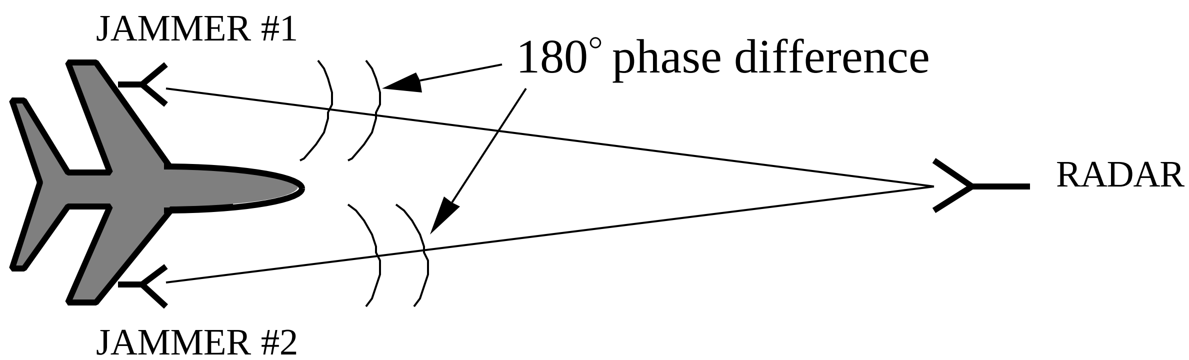
Bistatic RCS of a $5l$ square flat plate using the physical optics approximation





Cross Eye Jamming (1)

The cross eye technique uses two jammers to produce a large phase error across the radar's antenna aperture:



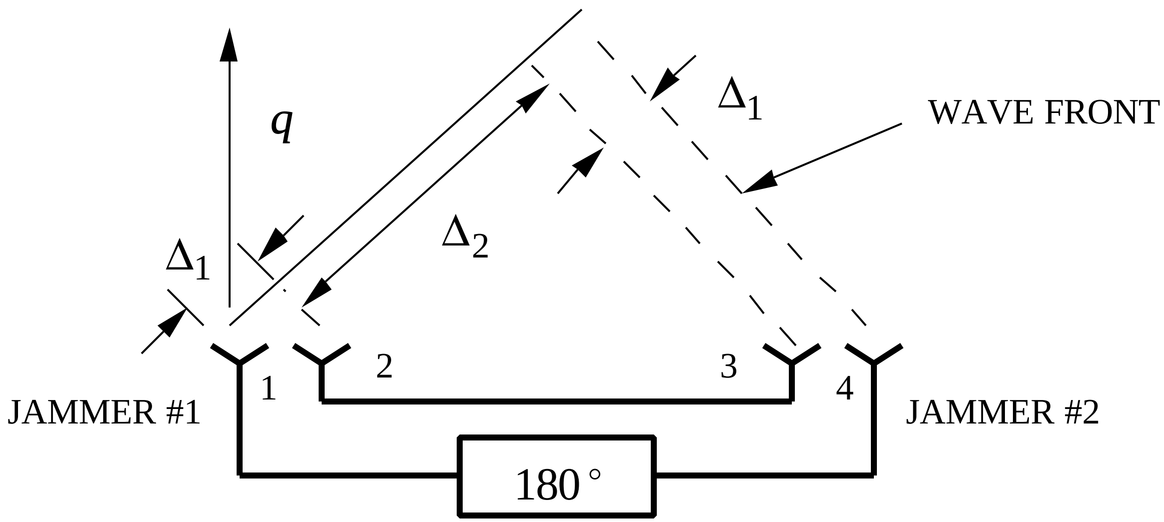
The jammers create two apparent scatterers that are out of phase with the following results:

	Passive Target	With Cross Eye
Σ Channel	Max	Null
Δ Channel	Null	Max

Tolerances required for the microwave network: Phase: ~ 0.3°
Amplitude: ~ 0.05 dB

Cross Eye Jamming (2)

1. Radar wave arrives at an angle q
2. Path difference between two adjacent elements (1-2 and 3-4) is Δ_1
3. Path difference between two inner most elements (2-3) is Δ_2
4. Line length between inner-most elements is L; between outer most elements $L+p$

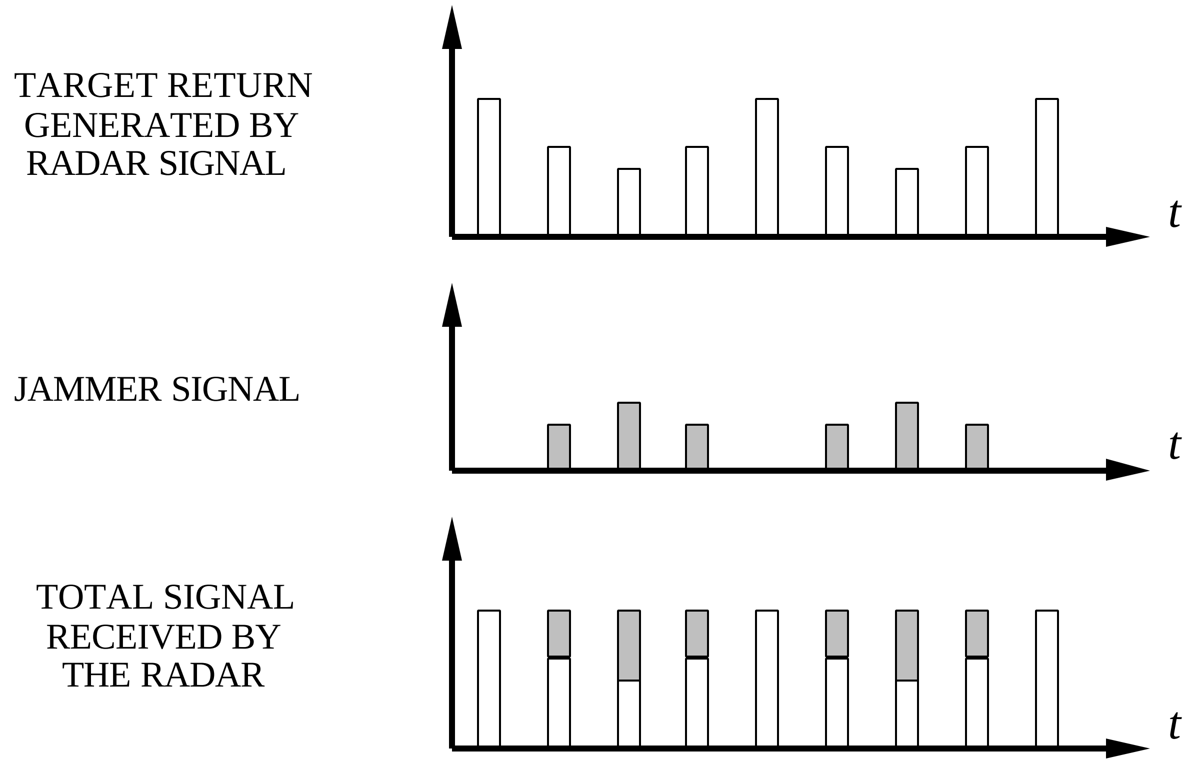


Signal path to and from radar:

$$\left.\begin{array}{l}\text{Outer elements}: \Phi_{14} = \underbrace{R + 2\Delta_1 + \Delta_2}_{\text{TO \#1}} + L + p + R \\ \text{Inner elements}: \Phi_{23} = \underbrace{R + \Delta_1 + \Delta_2}_{\text{TO \#2}} + L + \underbrace{\Delta_1 + R}_{\text{FROM \#3}}\end{array}\right\} \Rightarrow \Phi_{14} + \Phi_{23} = 0$$

ECM for Conical Scanning

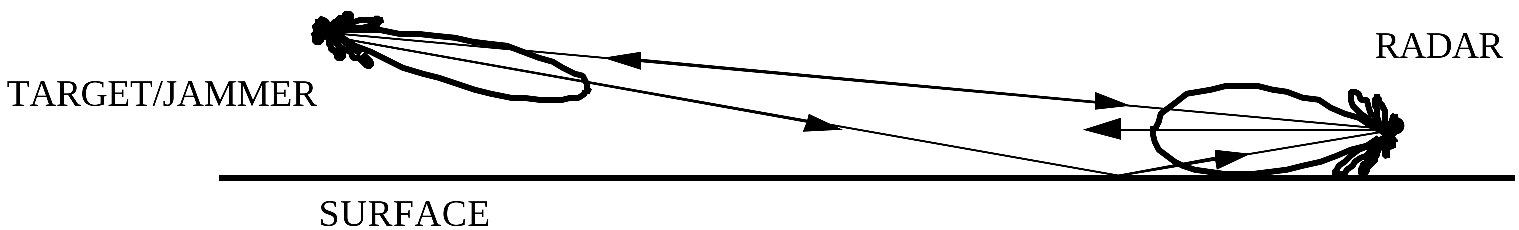
Conical scan is susceptible to ECM. A jammer can sense the radar's modulation and compensate for it. Therefore the radar believes its antenna is "on target" when in fact it is not.



It is usually sufficient for the jammer to just change the modulation (level or period) to spoof the radar.

Ground Bounce ECM

A jammer illuminates a ground spot. The radar receives a return from the target and the ground spot. The radar will track the centroid of the returns, which is an angle determined by a weighted combination of the two signals. The centroid will be in a direction closer to the strongest signal. Therefore the jammer signal must overpower the target return to defeat the radar.



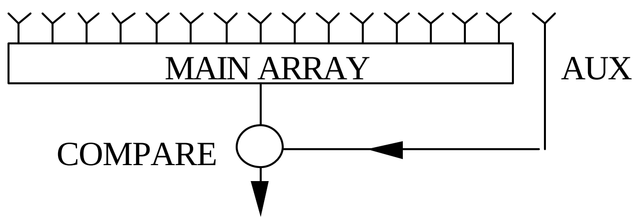
Ground bounce ECM is usually only applied at low altitudes where a strong controlled reflection can be generated.

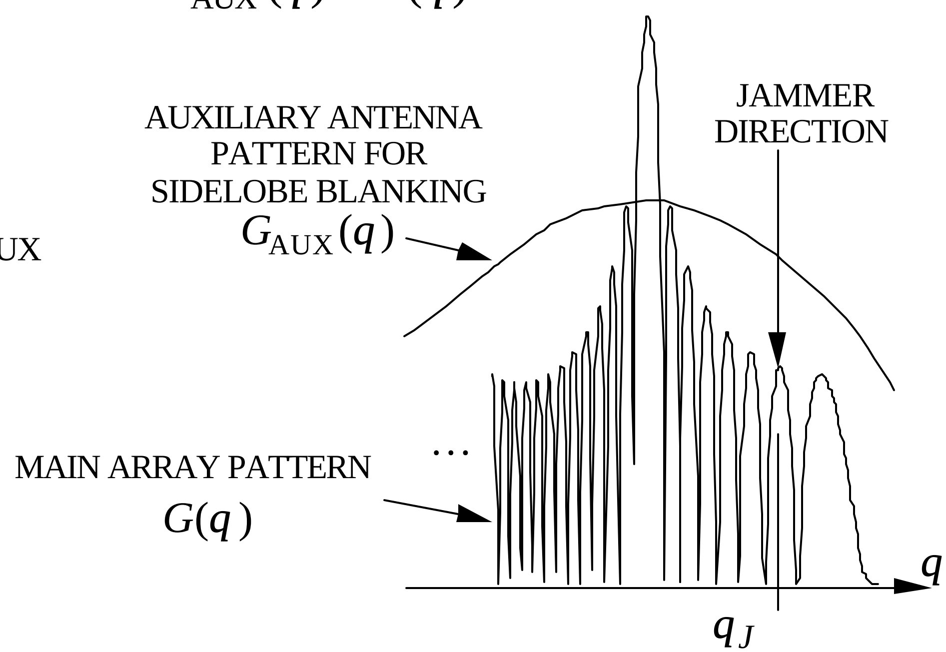
Suppression of Sidelobe Jammers (1)

Techniques to defeat sidelobe jammers:

1. antenna sidelobe reduction
2. multi-channel receiver techniques:
    a) sidelobe blanking: blank the main receiver channel (i.e., turn it off) if a signal arrives via a sidelobe

Turn off the receiver for angles where $G_{\mathrm{AUX}}(q) > G(q)$

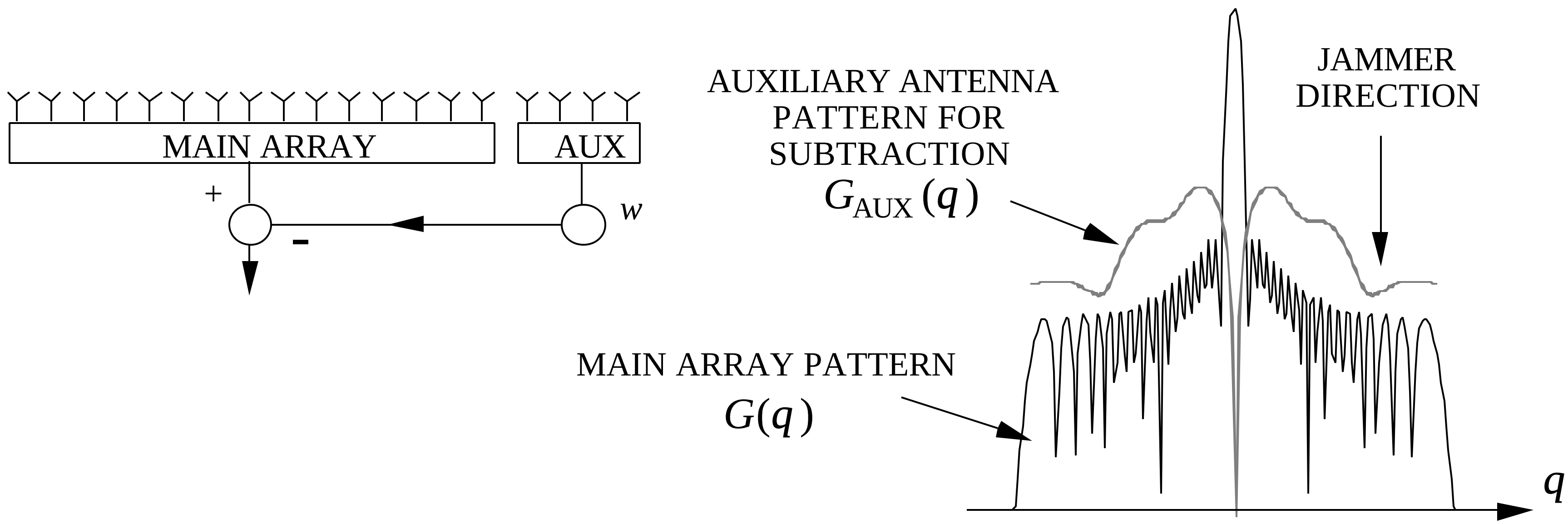




Suppression of Sidelobe Jammers (2)

b) coherent sidelobe cancelers (CSLC): coherently subtract the signal received via the sidelobes from the main channel signal

A CSLC requires an auxiliary antenna pattern with a null colocated with the main array beam maximum.



CSLC Equations for an Array Antenna

For simplicity neglect the element factor

$q_J =$ jammer angle
$AF(q_J) =$ main antenna array factor in the direction of the jammer
$AUX(q_J) =$ auxiliary antenna pattern in the direction of the jammer

Compute the complex weight:

$$y(q_J) = AF(q_J) - w \cdot AUX(q_J) \equiv 0$$

or, assuming that $AUX(q_J) \neq 0$,

$$w = \frac{AF(q_J)}{AUX(q_J)}$$

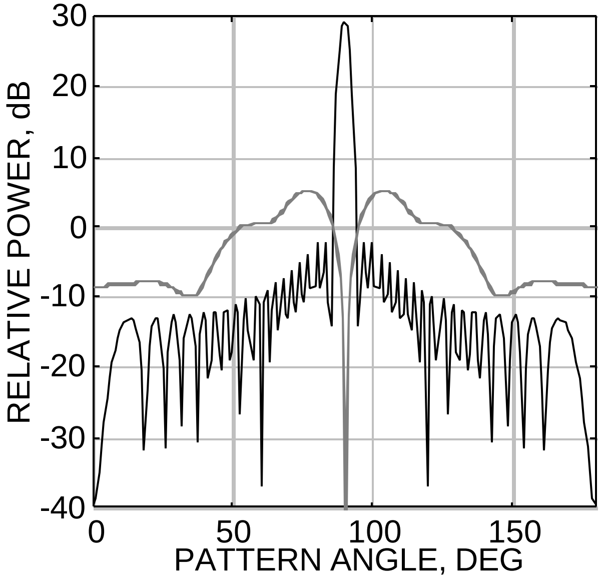
If $AUX(q_J) > AF(q_J)$ then $|w| \leq 1$. The array response at an arbitrary angle q is

$$y(q) = AF(q) - \frac{AF(q_J)}{AUX(q_J)} AUX(q)$$

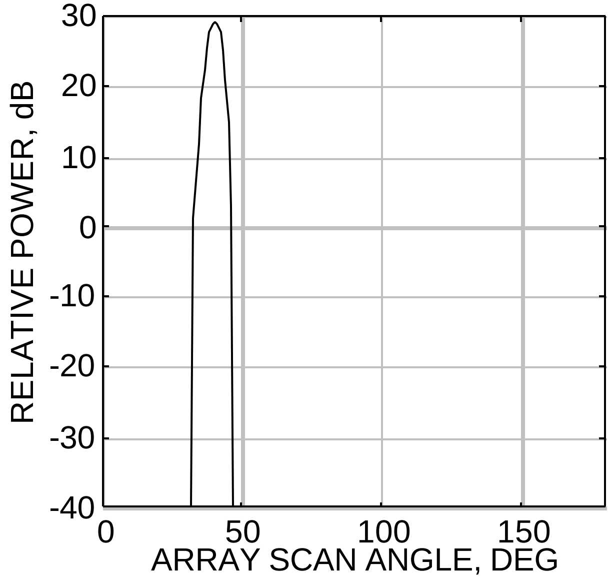
CSLC Performance

Example of CLSC performance for a 50 element array with $d = 0.4\,l$. The auxiliary array has 8 elements with "phase spoiling" to fill in the pattern nulls.

MAIN ARRAY AND AUXILIARY
ANTENNA PATTERNS

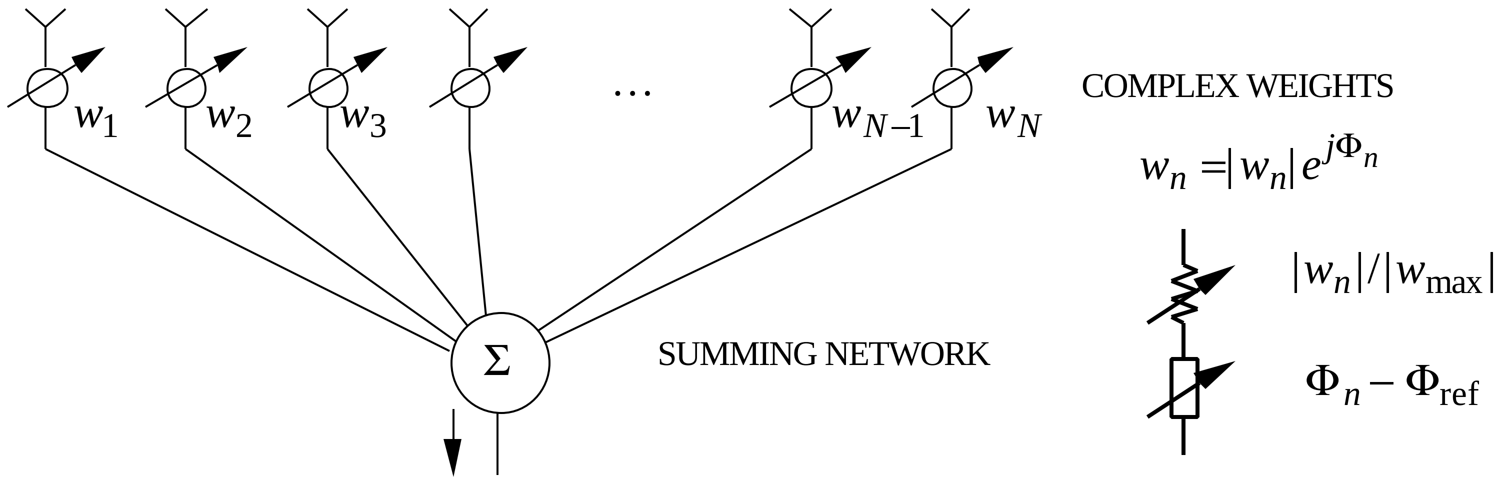


ARRAY RESPONSE FOR
A JAMMER AT 40 DEGREES



Adaptive Antennas

Adaptive antennas are capable of changing their radiation patterns to place nulls in the direction of jammers. The pattern is controlled by adjusting the relative magnitudes and phases of the signals to/from the radiating elements. Adaptive antenna model:

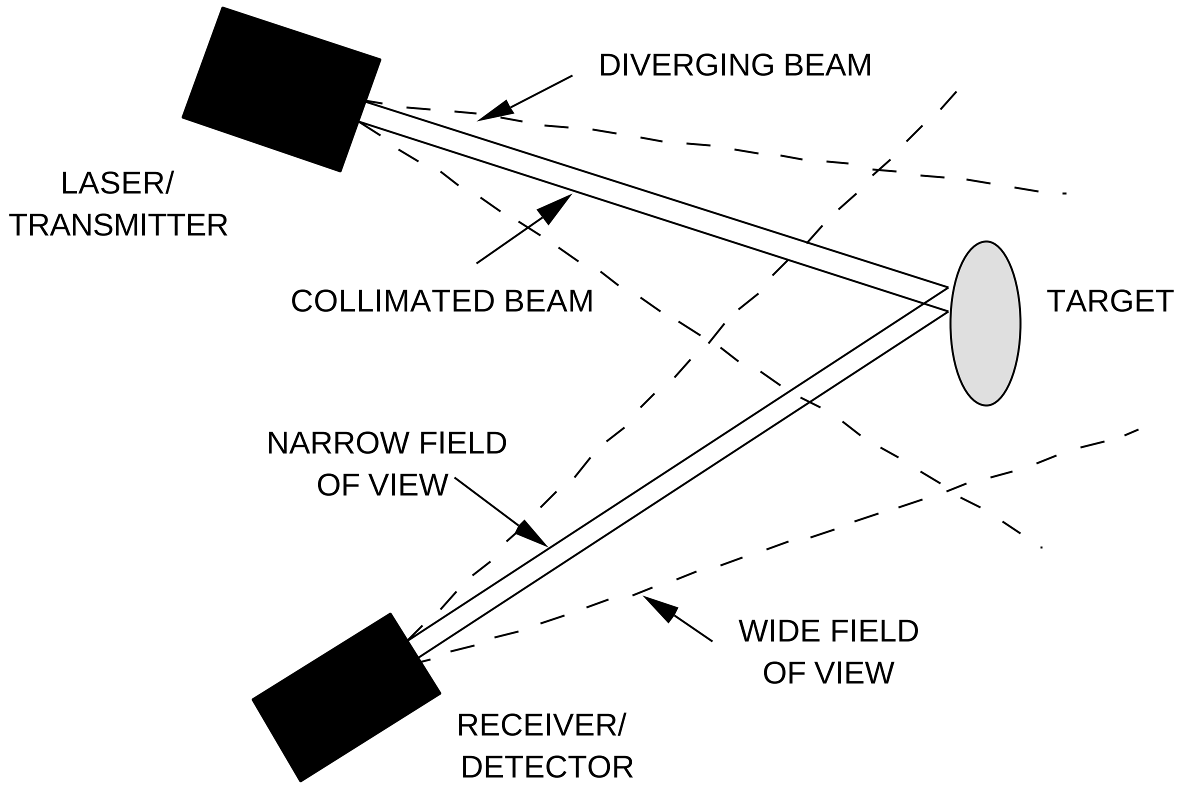


In principle, a N element array can null up to $N-1$ jammers, but if the number of jammers becomes a significant fraction of the total number of elements, then the pattern degrades significantly.

The performance of an adaptive array depends on the <u>algorithm</u> (procedure used to determine and set the weights). Under most circumstances the antenna gain is lower for an adaptive antenna than for a conventional antenna.

Laser Radar (1)

Laser radar (also known as lidar and ladar) operates on the same principle as microwave radar. Typical wavelengths are 1.06 and 10.6 mm. Atmospheric attenuation is a major concern at these frequencies. Laser radars are shorter range than microwave radar. Typical radar/target geometries:



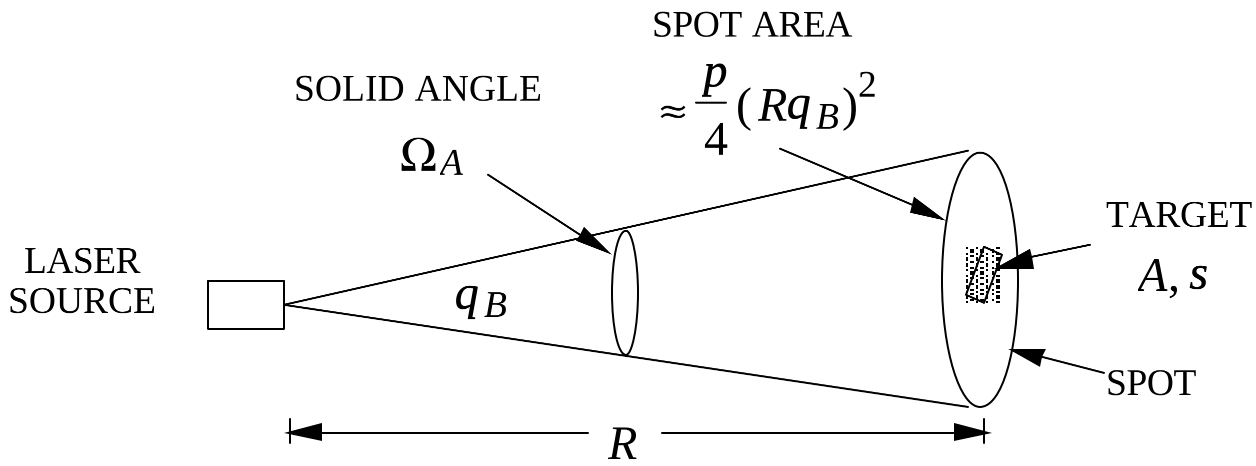
Laser Radar (2)

Advantages, disadvantages, and uses of laser radar:

- Small wavelength permits accurate range measurement
- Narrow beams and fields of view allows precise direction (pointing) information
- Narrow beams and fields of view implies poor search capability
- Laser radars are generally used in conjunction with other sensors:
  1. With infrared search and tracking (IRST) and thermal imaging systems to locate threats in volume search
  2. Used with microwave radar to improve range and angle information
- Atmospheric effects are very important:
  1. Absorption by gas molecules
  2. Scattering of light out of the laser beam by particles
  3. Path radiance (the atmosphere emits its own energy which appears as noise.
- Typical detection range of ground based system is ~ 10 km; for spaceborne systems it is thousands of km due to the absence of atmospheric losses.

Laser Radar (3)

Consider the case where the target is completely illuminated:



The laser beam solid angle is $\Omega_A = \dfrac{A_{\text{SPOT}}}{R^2} = \dfrac{pq_B^2}{4}$

The gain of the transmit optics is $G_t = \dfrac{4p}{\Omega_A} = \dfrac{16p}{q_A^2}$

The target is very large in terms of wavelength. Therefore, assume that the target only scatters the laser energy back into the hemisphere containing the radar. Then the spreading factor is $1/\,2pR^2$ rather than $1/\,4pR^2$.

Laser Radar (4)

Target scattered power back at the receiver:

$$P_r = \frac{P_t G_t}{4\pi R^2} \cdot \sigma \cdot \frac{1}{2\pi R^2} \cdot A_{er}$$

The area of the receive optics is A_{er}. Assume that the transmit and receive optics are identical

$$A_{er} \approx A_r = A_t = \pi \left(\frac{D}{2} \right)^2$$

The half power beamwidth is related to the optics diameter

$$\theta_B = 1.02 \lambda / D \approx \lambda / D$$

Introduce the optical efficiency ρ_o and atmospheric attenuation factor. The monostatic laser radar equation becomes:

$$P_r = \frac{8 P_t A_r^2 \sigma \rho_o}{\lambda^2 \pi^3 R^4} e^{-2\alpha R}$$

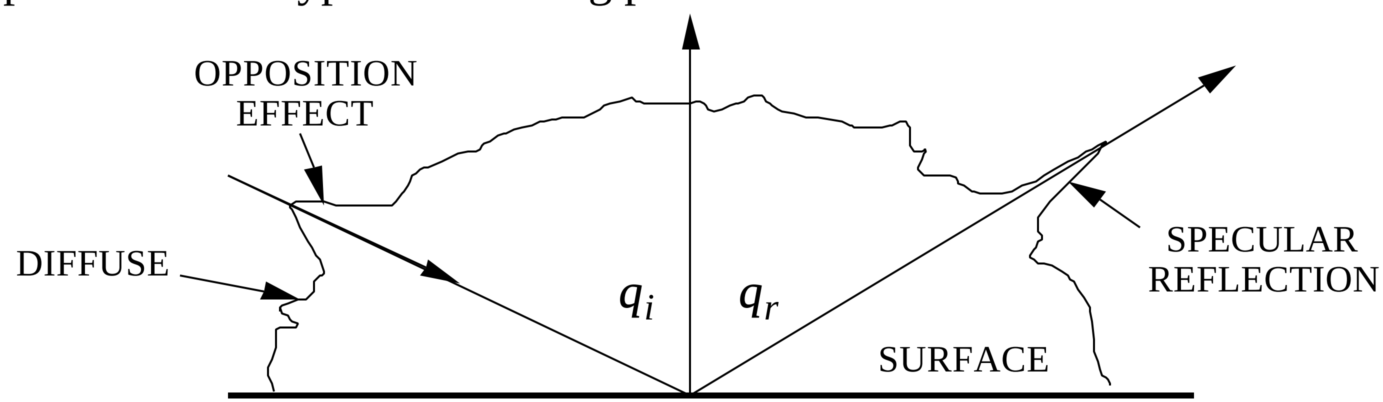
Laser Radar (5)

Laser cross section is identical to RCS:

$$s = \lim_{R \to \infty} 4p\, R^2 \frac{\left|\vec{W}_s\right|}{\left|\vec{W}_i\right|}$$

Important differences:

1. In practice the limiting process is rarely satisfied because l is so small.
2. The laser beam amplitude is not constant over the entire target.
3. Target surfaces are very rough in terms of wavelength. <u>Diffuse scattering</u> dominates.
4. Target surfaces are not perfectly diffuse nor uniform scatterers. The <u>bidirectional reflectance distribution function</u> (BRDF) characterizes the surface reflectivity as a function of position on the target surface, incidence direction, scattering direction, and polarization. Typical scattering pattern from a diffuse surface:

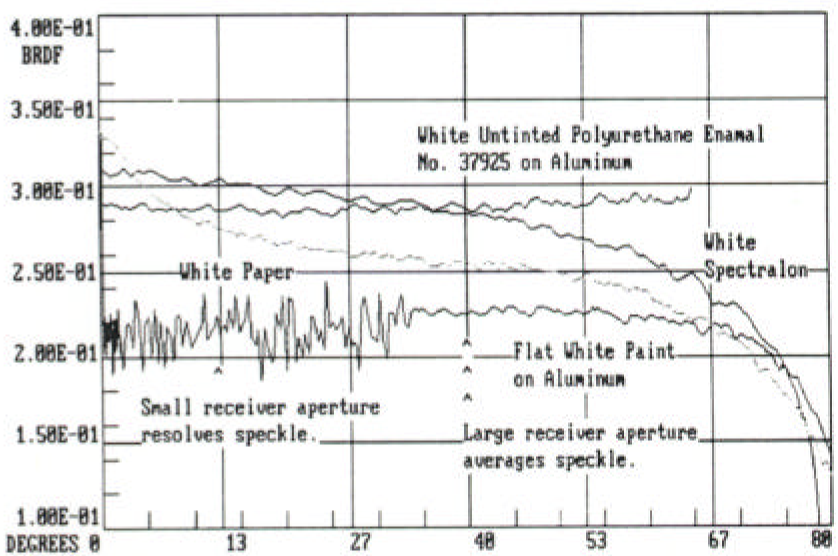


Laser Radar (6)

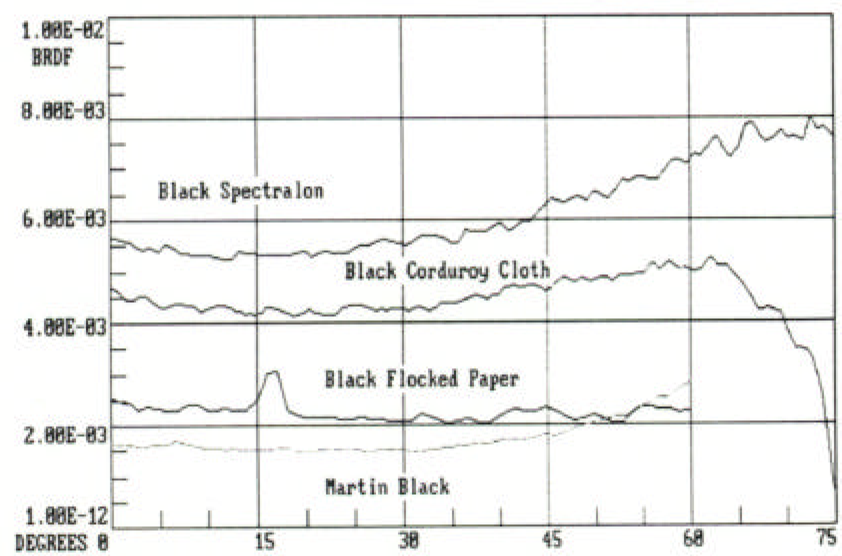
Examples of measured BRDFs at 0.633 micrometers

(from J. Stover, *Optical Scattering*)

White diffuse surfaces

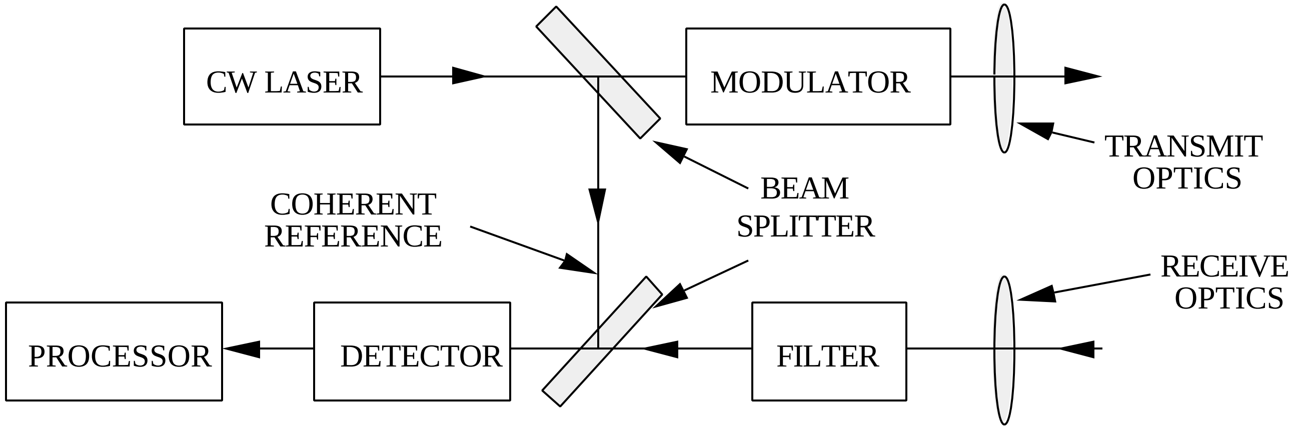


Black diffuse surfaces

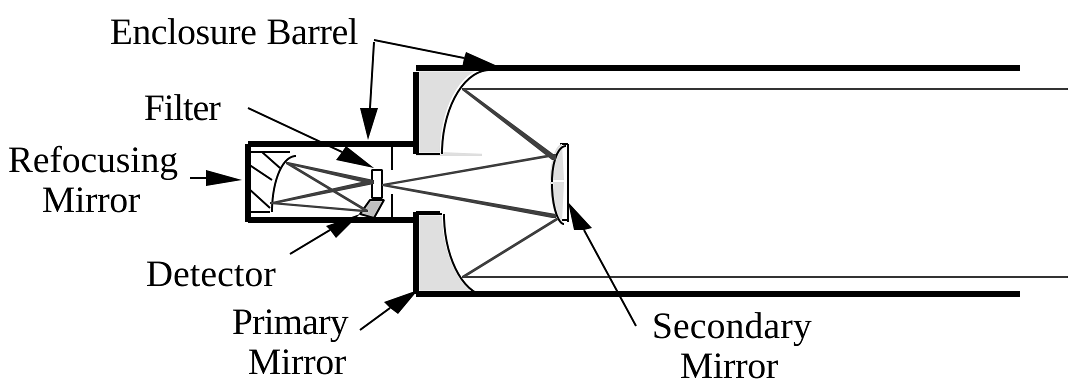


Laser Radar (7)

System block diagram:



Example of receive optics (Cassegrain reflecting system):



Laser Radar (8)

Laser seeker

Room

Laser radar image of room

Image resolution test panel (USAF)

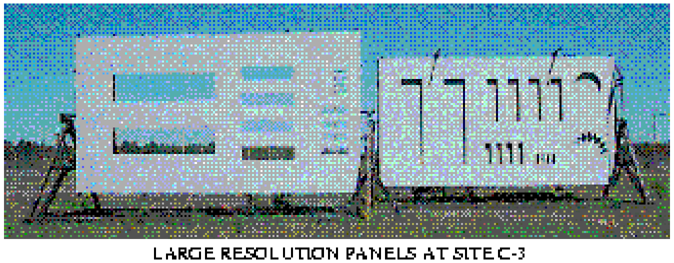
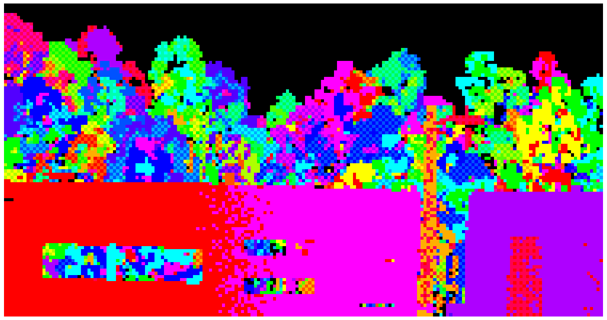


Image of test panel



Ground Penetrating Radar (1)

Ground penetrating radar (GPR), also known as subsurface radar, refers to a wide range of EM techniques designed to locate objects or interfaces buried beneath the Earth's surface. Applications that drive the system design include:

Application	Depth/range of interest
archeology	short to medium
wall thickness and hidden objects in walls*	short
unexploded ordinance and mines	short to medium
pipes and underground structures	medium
ice thickness	long

short: $d < 1/2$ m

medium: $1/2 \text{ m} < d < 25$ m

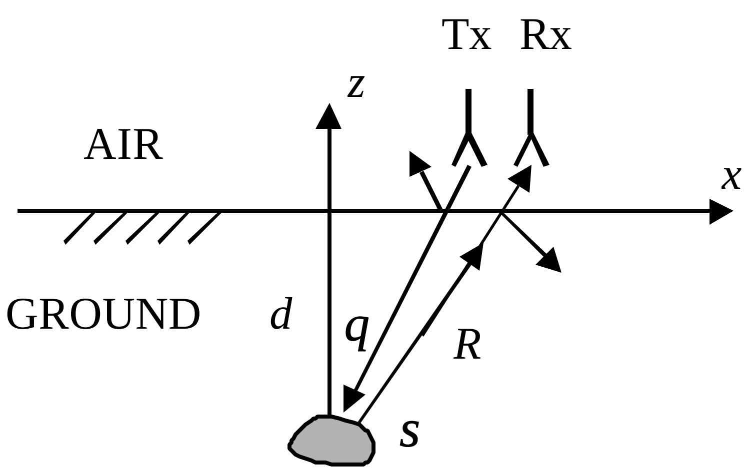
long: $d > 25$ m to hundreds of meters

*Radars for hidden object detection have requirements similar to those of ground penetrating radars.

Ground Penetrating Radar (2)

In essence, the same techniques as conventional free space radar can be used, but there are four unique issues to be addressed:

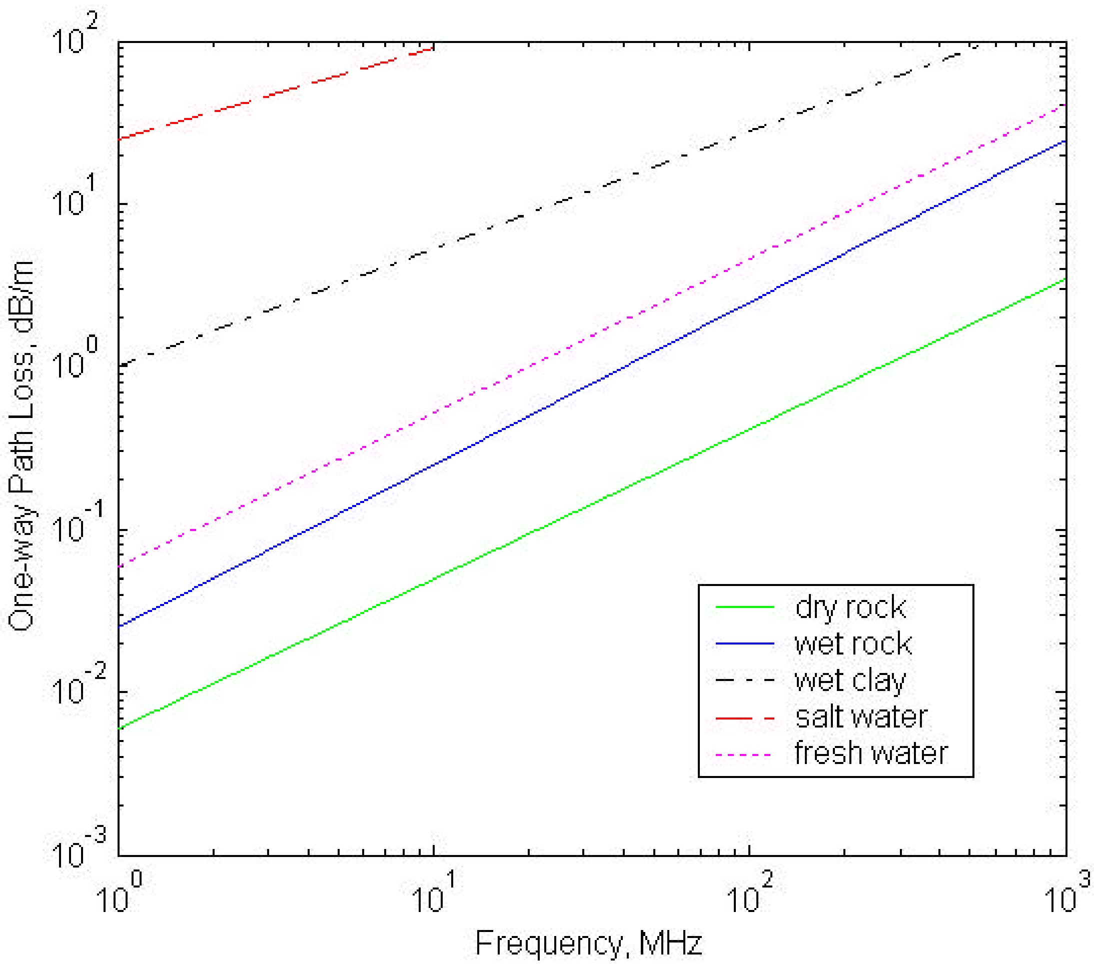
1. Efficient EM coupling into the ground
2. Adequate penetration of the radiation through the ground; ground is lossy, particularly above 1 GHz
3. Sufficient scattering from targets (dynamic range)
4. Adequate bandwidth with regard to resolution and noise levels



- Quasi-monostatic geometry shown
- Large reflection from the surface is clutter
- Ground loss can be extreme. Examples at 1 GHz:

wet clay	100 dB/m
fresh water	40 dB/m

Ground Penetrating Radar (3)

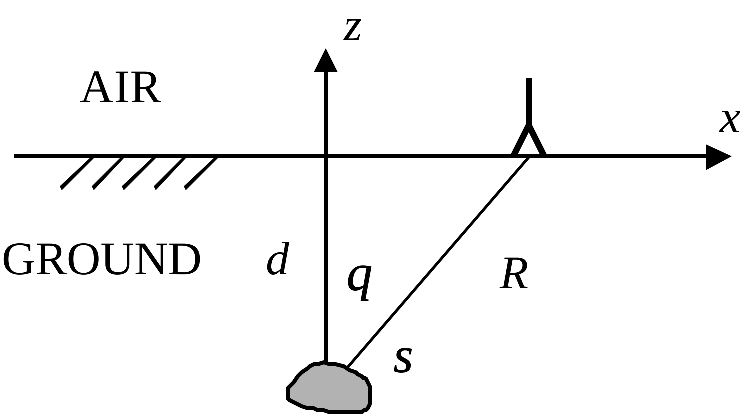


The major design consideration is the attenuation in the ground.

After figure from *Understanding Radar Systems* by Kingsley and Quegan

Ground Penetrating Radar (4)

Horizontal resolution can be obtained in several ways. One method is based on the received power distribution as the radar moves over the target.



- The received power is

$$P_r \propto \frac{e^{-4aR}}{R^4}$$

where a is the one-way voltage attenuation constant.

- If d and x are known then $R = \sqrt{d^2 + x^2}$ can be substituted.

- The attenuation constant is obtained from L, the "loss in dB per meter" quantity

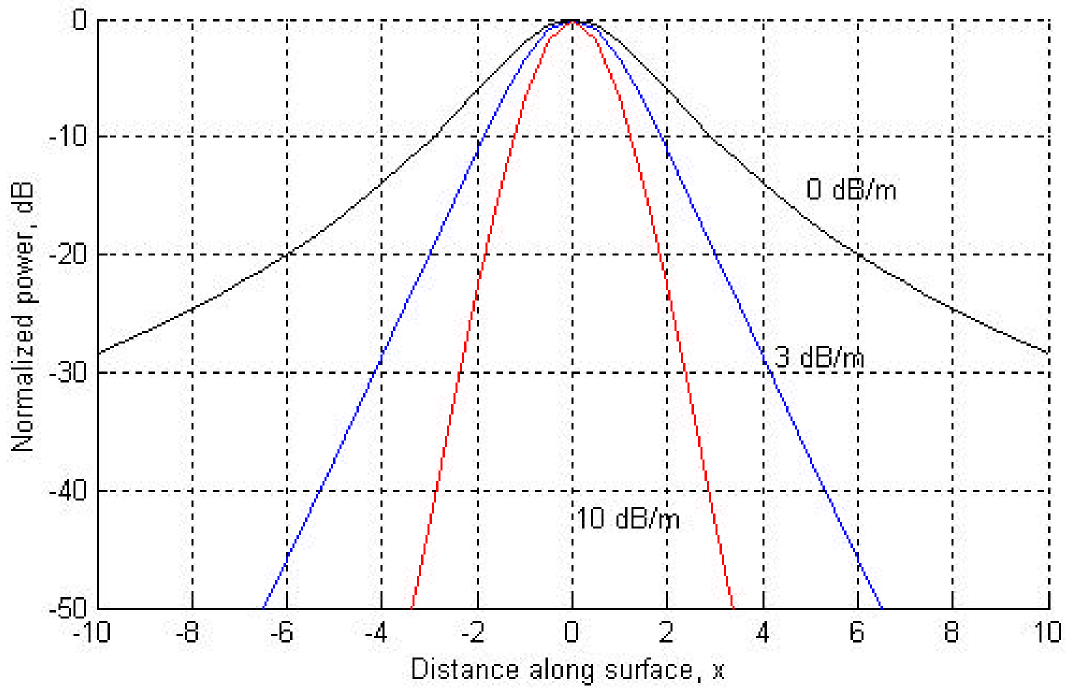
$$L = 20\log\left(\frac{E \text{ at 1 m depth}}{E \text{ at surface}}\right)$$
$$= 20\log\left(e^{-a\cdot 1}\right)$$

Therefore,

$$a = -\ln\left(10^{-L/20}\right)$$

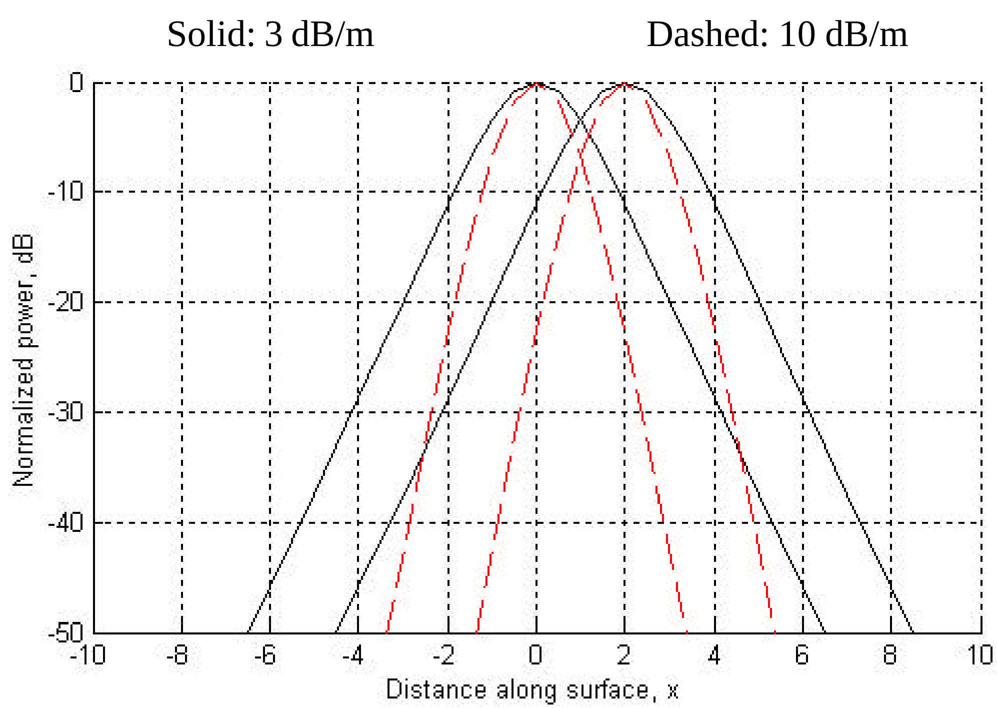
Ground Penetrating Radar (5)

Example: Return from a target at $x = 0$ ($d = 2$ m) as the radar moves along the ground for several ground attenuation values.



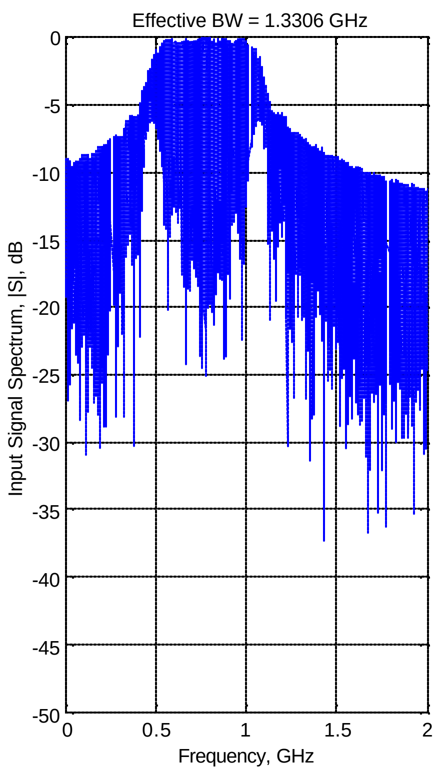
Ground Penetrating Radar (6)

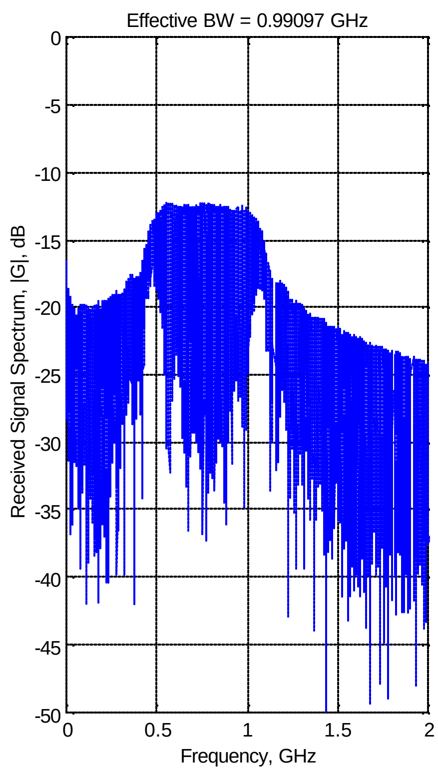
Example: Returns from two equal RCS targets at x = 0 and 2 meters for various ground loss (d = 2 m). Note that higher loss actually improves horizontal resolution. Increasing the loss per meter has the same effect as narrowing the antenna beamwidth.



Ground Penetrating Radar (7)

Example: Stepped frequency waveform (12 pulses, frequency step size 50 MHz per pulse, start frequency 500 MHz, PRF 10 MHz, pulse width 0.01 microsecond)





The ground loss has reduced the effective bandwidth B_e by about 25 percent. By the uncertainty relation

$$B_e t_e \geq p$$

Since the range resolution is approximately

$$\Delta R \approx \frac{c}{2} t_e$$

the range cell has also been increased by about 25 percent due to the ground loss.

Ground Penetrating Radar (8)

Cross-range can be determined in several ways:

1. narrow antenna beamwidth: Usually not practical because of the low frequencies required for ground penetration. Small "illumination spot" required for a 2D image.
2. Power distribution variation as the antenna moves over the ground, as illustrated in chart GPR (6): Performance depends on ground loss, variations in the scattering cross sections of objects, depth and separation of objects, etc. 2D transversal required for a 2D image.
3. SAR techniques: Ground loss limits the synthetic aperture length because it has the same effect as narrowing the beamwidth (i.e., cannot keep the scatterer in the antenna field of view). 2D transversal required for a 2D image.

Mobile ground penetrating radar in operation

Overall, GPR is probably the most challenging radar application.

GPR system design is specific to the particular application.